INTRODUCTION

Alluvial and canyon-bound reaches of the Colorado River in western Colorado and eastern Utah provide important habitat for four endangered fishes in the upper Colorado River basin- the Colorado pikeminnow (*Ptychocheilus lucius*), the razorback sucker (*Xyrauchen texanus*), the humpback chub (*Gila cypha*) and bonytail (*Gila elegans*). Success in recovering these fishes will depend in large part on the maintenance and improvement of existing habitats within several key reaches of the Colorado River, including the 15-mile and 18-mile reaches near Grand Junction, Colorado. Along with the lower reaches of the Gunnison River, the 15- and 18-mile reaches represent the upper limit of the current range of Colorado pikeminnow and razorback sucker on the mainstem of the Colorado River; humpback chub are found in incised bedrock reaches further downstream (Black Rocks and Weswater Canyon). The 15- and 18-mile reaches are characterized as having a mildly sinuous channel pattern with varying amounts of complexity; bankfull depths average 2.5-3 m and substrate grain sizes vary from fine gravel to cobbles [*Pitlick et al.*, 1999; *Pitlick and Cress*, 2002]. This combination of physical characteristics, together with light and nutrient availability, provides for relatively high levels of primary and secondary production in comparison to reaches further downstream, and a relative abundance of native prey fishes (flannelmouth sucker and bluehead sucker) [*Osmundson et al*., 2002]. Presumably, it is the availability of habitats in the 15- and 18-mile reaches, and the abundance of potential prey fishes, that draw Colorado pikeminnow upstream as they mature. Razorback sucker were once found in the 15- and 18-mile reaches, but these fish are now very rare and their habitat requirements are not well understood. Further migration by either species to habitats upstream of the 15-mile reach is presently limited by a series of low-head diversion dams near Palisade, Colorado, thus management and monitoring of conditions within the 15-mile reach is an important priority.

Streamflows into the 15-mile and 18-mile reaches are regulated by a series of reservoirs and diversions. At present there are 24 reservoirs with a storage capacity greater than 5,000 acre-feet (6.2×10^6 m^3) upstream of the Colorado-Utah state line [*Liebermann et al.*, 1989]. These reservoirs are scattered throughout the upper basin; individually, they are not large in comparison to other dams in the Colorado-Green River system (e.g. Flaming Gorge or Glen Canyon), but collectively they have the capacity to store the equivalent of about half the annual flow of the Colorado River at the Colorado-Utah state line [*Pitlick et al.*, 1999]. Reservoir construction and operations have altered the timing and magnitude of peak flows in the 15- and 18-mile reaches significantly. Since 1950, annual peak discharges of the Colorado River, and its major tributary the Gunnison River, have decreased by 30-40% [*Pitlick et al*., 1999]. In addition to altering peak flows, upper basin reservoirs store spring runoff which is diverted to municipalities and projects east of the continental divide. Diversions remove an average of about 14% of the annual native flow of the Colorado River above the 15-mile reach, although in some years as much as 30% of the annual flow is taken out of the upper basin [*Osmundson* et al., 2002].

The primary geomorphic effect of water-management activity in the Colorado River basin has been to reduce the sediment-transport capacity of the river. Analysis of suspended sediment data from gauging stations operated by the U.S. Geological Survey (USGS) indicates that surface erosion of sedimentary rocks in areas immediately upstream of the key reaches contributes a large proportion of the sediment carried by the Colorado River [*Iorns et al*., 1965; *Liebermann et al*., 1989; *Pitlick and Cress*, 2000]. Most of the reservoirs in the upper Colorado River basin are well above these areas, and therefore have little effect on the amount of sediment delivered. However, because of reductions in peak flows, both the Colorado River and the Gunnison River have lost some of their capacity to carry sediment. Changes in transport capacity over the long term have caused sediment to accumulate in the channel, causing it to become narrower and less complex overall. *Van Steeter and Pitlick* [1998] report that between 1937 and 1993 the main channel of the Colorado River narrowed by an average of about 20 m, and one quarter of the area formed by side channels and backwaters had been lost.

Although water-management activities have caused persistent, long-term changes in the hydrology of the Colorado River, the potential exists to coordinate reservoir operations in the upper basin to periodically augment spring snowmelt flows and enhance peak discharges in the 15- and 18-mile reaches. The function and importance of peak flows were summarized in the recommendations given previously by *Pitlick and Cress* [2000]:

- Flows equal to or greater than 1/2 the bankfull discharge are needed to mobilize gravel and cobble particles on a widespread basis, and to prevent fine sediment from accumulating in the bed. Flows greater than 1/2 the bankfull discharge also transport between 65 and 78% of the annual sediment load of the Colorado River. Flows greater than 1/2 the bankfull discharge thus provide several important geomorphic functions, assuming they occur with sufficient frequency. In the 20-year period from 1978 to 1997, daily discharges equaled or exceeded 1/2 the bankfull discharge an average of about 30 days per year. Given these results and supporting information about what these discharges accomplish, we recommend that flows equal to or greater than 1/2 the bankfull discharge should occur with an average frequency of at least 30 days per year.

- Flows equal to the bankfull discharge produce average shear stresses that are about 1.5 times the critical shear stress for bed load transport; this discharge is sufficient to fully mobilize the bed material and maintain the existing bankfull hydraulic geometry. On the basis of data from the 20-year period from 1978 through 1997, we recommend that flows equal to or greater than the bankfull discharge should occur at least 5 days per year, on average.

- The single most important thing that can be done to maintain habitats used by the endangered fishes is to assure that sediment supplied to the critical reaches continues to be carried downstream. Sediment that is not carried through will accumulate in low velocity areas, resulting in further channel simplification and narrowing.

The recommendations above emphasize physical processes associated with particular flows, and stress the importance of sediment transport in shaping and maintaining habitats used by the endangered fishes. Use of individual habitats within the 15- and 18-mile reaches varies with fish species and life stage [*LaGory et al.*, 2003], but most all habitats are affected by the movement of sediment. Spawning habitats formed by gravel and cobble substrates (riffles, shoals, or bars) require periodic flushing to remove interstitial fine sediment [*Pitlick and Van Steeter*, 1998; *Osmundson et al*., 2002]. Low velocity channel-margin habitats, including backwaters and secondary channels, require continued transport of fine sediment to prevent deposition and further channel simplification [*Osmundson et al*., 1995; *Van Steeter and Pitlick*, 1998]. Disturbance of elevated surfaces by high flows is necessary to limit establishment of vegetation and stabilization of channel bars.

The present study was initiated to assess the geomorphic effects of coordinated reservoir operations, and to develop a better understanding of the timing of sediment supply and sediment transport in key reaches of the Colorado River. The specific objectives of this study were to:

1. Monitor rates of channel change and assess the geomorphic effects of coordinated reservoir releases and normal snowmelt flows.

2. Define the window of time of peak sediment delivery from unregulated tributaries.

3. Verify discharge thresholds for coarse-sediment transport.

6. Examine processes of fine-sediment transport and deposition on the falling limb of the hydrograph.

7. Develop a matrix which can be used by the coordinated reservoir operations group to tailor operations to target multiple objectives of habitat maintenance and creation.

6. Provide data on thresholds and durations of discharges that perform important geomorphic functions so that biologists can integrate this information with biological information and refine flow recommendations as necessary.

Field measurements coinciding with the late spring-early summer period of peak runoff were taken at various locations in the 15- and 18-mile reaches from 1998 through 2004. An array of techniques was used to monitor changes in channel geomorphology and the movement of fine and coarse sediment in response to different flow levels. Results of this work will aid in refining flow recommendations so that, in the future, reservoir operations can be adjusted and releases can be timed to provide the greatest benefit to the endangered fishes.

STUDY AREA

Field studies for this project focused on conditions within specific segments of the 15- and 18-mile reaches of the Colorado River near Grand Junction, Colorado (Fig. 1). The general setting and physical characteristics of these reaches are described in detail in a number of previous reports and papers [*Osmundson and Kaeding*, 1991; *Osmundson et al.*, 1995; *Van Steeter and Pitlick,* 1998; *Pitlick and Van Steeter*, 1998; *Pitlick et al*., 1999; *Pitlick and Cress,* 2000*; Pitlick and Cress*, 2002; *Osmundson et al.*, 2002]. The channel pattern of the Colorado River in the 15- and 18-mile reaches is mildly sinuous. In a number of places the channel splits into two or more branches, resulting in a braided-like pattern; however, in a long-term sense, this segment of the Colorado River is geomorphically stable, meaning that in most places the overall pattern and position of the channel are changing relatively slowly.

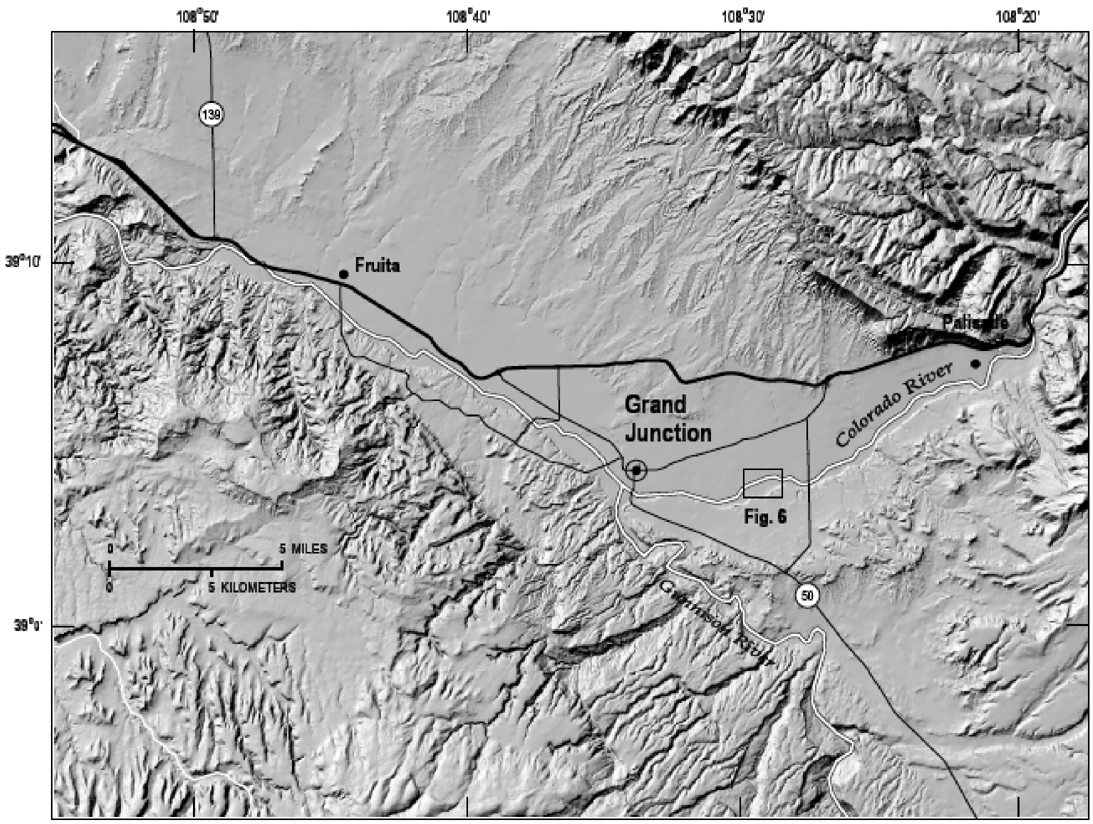


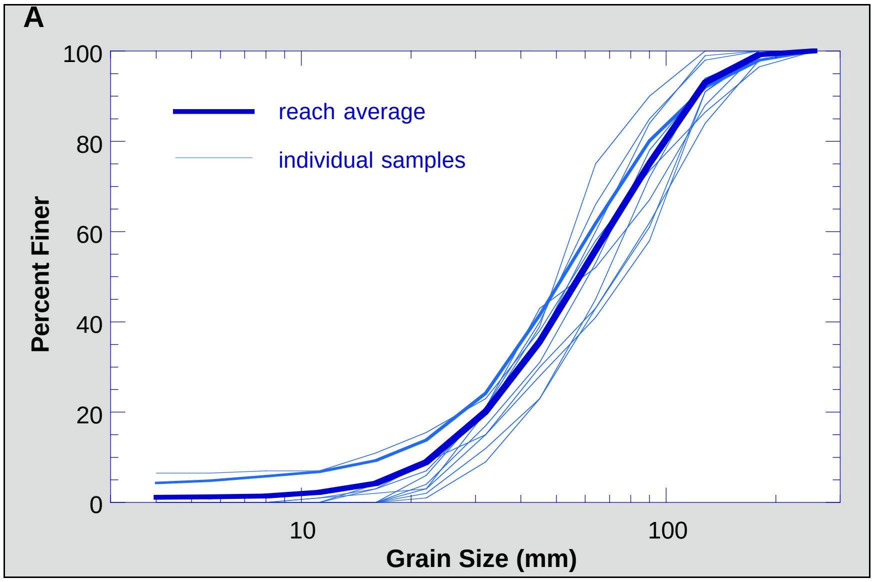
Figure 1. Location of the Colorado River and Gunnison River near Grand Junction, Colorado. The 15-mile reach includes the channel segment between Palisade, CO, and the confluence with the Gunnison River. The 18-mile reach includes the segment from the Gunnison River to Loma, CO. The inset box, labeled Figure 6, indicates the location of the reach used for detailed studies of sediment transport and channel change near river kilometer (RK) 283.

Floodplains and low lying alluvial surfaces border the channel of the Colorado River through much of the study area (Fig. 2). In a number of places, particularly in the 15-mile reach, the river flows against steep bluffs underlain by Mancos shale bedrock. Elsewhere, the channel is confined locally by concrete rip rap and artificial levees. The constraints imposed by levees and rip rap are most noticeable in the channel reaches in the immediate vicinity of Grand Junction. Outside of Grand Junction, most of the bank stabilization efforts have been initiated by local land owners, who follow the practice of placing concrete rip rap along the banks to slow erosion.

Floodplains and low-lying bar surfaces are covered with a mix of recent and mature vegetation. Dominant woody species include native sandbar willow (*Salix exigua*) and cottonwood (*Populus deltoides*), and non-native tamarisk (*Tamarix chinensis*) and Russian olive (*Elaeagnus angustifolia*). Sustained low flows during the 2002-2004 drought have allowed both native and non-native plants to colonize mid-channel bars and bank areas that would normally be inundated for several weeks during the period of snowmelt runoff (illustrated in the figure below and on the front cover).

Figure 2. Upstream view of the Colorado River near RK 283 (RM 176) in the 15-mile reach.

The channel bed material in the 15- and 18-mile reaches consists of gravel- and cobble-sized sediment. The median grain size, D_{50}, of the bed surface sediment (armor layer) in the 15-mile reach, as determined from point counts of 100-200 rocks on exposed gravel bars, ranges from 40 to 80 mm, with an average D_{50} of 58 mm (Fig. 3a). The D_{50} of the bed surface sediment in the 18-mile reach ranges from 40 to 70 mm, with an average of 51 mm (Fig. 3b).



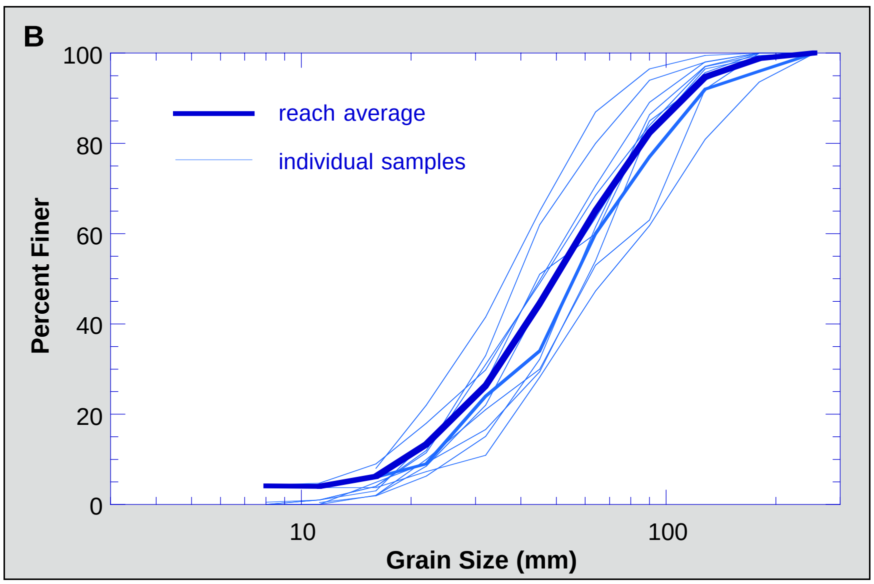


Figure 3. Grain size distributions of the bed surface (armor) layer based on pebble-counts in different locations in (a) the 15-mile reach and (b) the 18-mile reach. The light blue lines indicate individual samples, while the dark blue lines indicate the average for each reach.

Average channel gradients of the 15-mile and 18-mile reaches were determined with a mapping-grade global positioning system (GPS). Readings of the water surface were taken with the GPS at evenly spaced, 0.8-km intervals along the channel. Subsequently, the raw data were corrected with differential post-processing techniques, using base-station measurements collected by the Mesa County Public Works Department. Post-processing of the field data reduces the vertical positional error to ± 0.5-0.3 m. These errors tend to be random and are small in comparison to the total drop in elevation through the study reaches (35-45 m). The GPS measurements show that the longitudinal profile of the Colorado River is very smooth between Palisade, CO, and Westwater, UT (Fig. 4). Average channel gradients determined from these measurements are 0.00175 in the 15-mile reach; 0.0013 in the 18-mile reach; and 0.0010 in the Ruby-Horsethief Canyon reach.

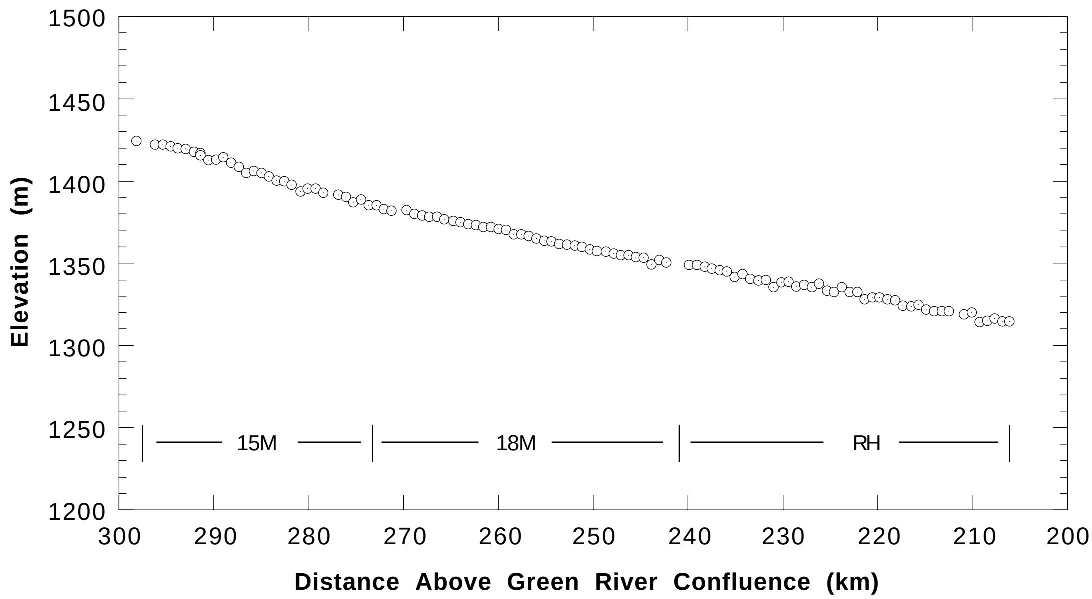


Figure 4. Longitudinal profile of the Colorado River between Palisade, CO, and Westwater, UT. Individual data points were measured with a mapping grade global positioning system (GPS). Distances are given in river kilometers (RK = 1.61 mile), measured upstream from the confluence of the Colorado River and the Green River. Bars below the data indicate boundaries between the 15-mile reach (15M), 18-mile reach (18M), and Ruby-Horsethief Canyon reach (RH). The Gunnison River joins the Colorado River at RK 275.

As noted in the introduction, natural streamflows of the Colorado River are regulated by a series of storage reservoirs and water diversions upstream of the study area. Most of the reservoirs in the upper Colorado River basin were constructed in the period between 1950 and 1966. These reservoirs were built primarily to store spring runoff, which is then moved through a series of tunnels and transbasin diversions to supply municipalities and irrigation projects on the east of the continental divide. Although reservoir operations affect both the timing and magnitude of peak snowmelt flows in the study area, runoff from unregulated tributaries is still sufficient to produce a prominent peak in the annual hydrograph. Runoff from late-summer thunderstorms can elevate streamflows and increase turbidity for several days. Peaks produced by these storms are generally small in comparison to the annual snowmelt peak.

The Colorado River carries moderately high sediment loads, increasing downstream from about 1.5 x 10^6 metric tons per year at the US Geological Survey (USGS) gauging station near Cameo, CO, to about 3.4 x 10^6 metric tons per year at the USGS gauging station near the Colorado-Utah state line [*Pitlick and Cress*, 2000]. At least 95% of the total annual sediment load consists of fine sediment (silt and sand) that is carried in suspension [*Pitlick and Van Steeter*, 1998]. Much of the fine sediment is derived from surface erosion of friable sedimentary rocks underlying the Roan Mesa. The contribution of fine sediment from this area remains high. Coarse sediment (cobble and gravel) is derived from local as well as distant sources. Although gravel is a minor component of the total annual sediment load of the Colorado River, this material forms the bed of the channel, and therefore provides habitat for benthic invertebrates as well as native and non-native fishes.

DATA SOURCES AND METHODS

Streamflow and Suspended Sediment

The USGS operates four streamflow gauging stations within the study area. These stations are used for continuous monitoring of river stage and streamflow, and periodic measurements of water quality, including water temperature, dissolved oxygen, dissolved solids, major ions, and suspended sediment. Gauging stations on the main stem of the Colorado River include: the Colorado River near Cameo (station no. 09095500, located in DeBeque Canyon); the Colorado River below Grand Valley Diversion near Palisade (station no. 09106150, located at the head of the 15-mile reach); and the Colorado River near the Colorado-Utah state line (station no. 09163500, located near the downstream end of Ruby-Horsethief Canyon). One station on the Gunnison River is also included in the analysis: Gunnison River near Grand Junction (station number 09152500). Streamflow data for the individual gauges are available for the following periods of record: Cameo gauge, 1934-present; Palisade gauge, 1990-present; State Line gauge, 1952-present; and the Gunnison River gauge, 1902-present.

Measurements of suspended sediment have been taken periodically at three of these four gauging stations. The sediment record from the Cameo gauge is the most complete; this data set includes 576 measurements of discharge and suspended sediment concentration between 1982 and 1998; 449 of these samples were analyzed to determine the fraction of suspended sediment finer than 0.0625 mm, which is the break between silt- and sand-size particles. The record from the Gunnison River gauge includes 306 measurements of discharge and suspended sediment concentration taken between 1959 and 1999; 120 of these samples were analyzed to determine the fraction of sediment finer than 0.0625 mm. The record from the State Line gauge includes 281 measurements of discharge and suspended sediment concentration taken between 1976 and 1999; 150 of these samples were analyzed to determine the fraction of sediment finer than 0.0625 mm.

Coordinated Reservoir Operations

From 1997-2000, representatives from various federal agencies and reservoir operators in the upper Colorado River basin participated in discussions to coordinate and modify reservoir operations to enhance spring peak flows in the 15-mile reach. The specific objectives of the coordinated reservoir operations program (CROS) were as follows:

> The objective of CROS is to coordinate bypasses of inflows from various reservoirs resulting in enhancement of habitat in the 15-mile reach of the Colorado River without exceeding the National Weather Service flood level of 26,600 ft^3/s at Cameo. These bypasses may have passed through the participating reservoirs during the runoff period. Coordinated reservoir operations moves those bypasses to the peak of the runoff hydrograph to enhance spring peak flows, which are important to spawning and improvement of aquatic food sources. Coordination and modification of operations are voluntary and occur within current authorizations and guidelines and without affecting project yields to either federal or non-federal reservoirs (*source*: Annual Summary of Coordinated Reservoir Operations for 1998 to Benefit the Endangered Fishes of the Upper Colorado River Basin, Colorado Water Conservation Board).

Timetables and procedures for coordinating reservoir operations were developed annually from 1997-2000 through a coordination committee composed of representatives from each of the participating agencies and reservoir operators. Prior to the start of spring snowmelt, hydrologic conditions within the upper Colorado River basin were assessed and the decision whether to modify reservoir operations was discussed. Measurements of the snowpack in 1997, 1998 and 1999 indicated that the snow-water equivalent and runoff in most parts of the basin would be near average, thus operations were adjusted in those years to bypass inputs to reservoirs. Plans were in place to bypass flows in 2000, however, unusually warm weather in early May caused a rapid reduction in snow-water equivalent throughout the basin and coordinated reservoir operations were called off that year.

Channel Geomorphology

Changes in channel geomorphology produced by normal and augmented streamflows were determined from (i) analysis of aerial photographs taken seven years apart and (ii) repeated surveys of channel cross sections in selected reaches.

Aerial Photographs: High quality color aerial photographs of the 15- and 18-mile reaches of the Colorado River were taken in August, 2000, for the purposes of comparison with an earlier set of photographs taken in September, 1993. The separate sets of photographs cover the same section of the Colorado River from Palisade to approximately Loma, CO (RK 300-250), and they were flown at the same scale (1: 6000), in late summer with the river flowing at similar discharges at the time of the photography. In 2000 the discharge in the 15-mile reach at the time of the photography was 36.6 m^3/s (1290 ft^3/s), which is nearly identical to the 1993 discharge of 37 m^3/s (1310 ft^3/s). In 2000 the discharge in the 18-mile reach at the time of the photography was about 115 m^3/s (4060 ft^3/s) which is 15% lower than the 1993 discharge of 135 m^3/s (4770 ft^3/s). Both sets of photographs were georeferenced by Positive Systems, resulting in seventeen total georeferenced mosaics. Eight mosaics from the 1993 data set and 9 mosaics from the 2000 data set were used to delineate channel characteristics. The aerial photographs were not orthorectified to account for flight angle or distortion effects; however, these effects were assumed to be minimal given the relatively low relief of the river and surrounding terrain in the study area. Georeferencing was done in UTM coordinates.

From the aerial photographs, a layer in ArcView was digitized to represent the boundaries between individual river miles (Fig. 5). The layer created in ArcView for these river miles stores the UTM coordinates from the mosaic of aerial photographs, thus allowing a single layer for river miles to be utilized on the aerial photographs from both years. This assures the comparison between years will be based on identical sections of channel. These river mile boundaries were verified between topographic maps and the aerial photos.

Figure 5. Segment of the Colorado River near Fruita, CO, RK 251, showing delineation of channel features (blue = main channel, green = side channels).

For each year, in each river mile, a separate layer was digitized to represent the main channel, side channels, and exposed channel bars. Thus each river mile for each year contains three different layers. The area of each channel feature was then computed for each river mile and compared between years. The digitizing of channel features was done by creating shapefiles for each layer (Fig. 5). These shapefiles were digitized by hand by zooming in on important channel features and carefully digitizing the features point by point along the boundary. More points were digitized near irregular boundaries and a typical channel reach contains several hundred digitized points to delineate individual features. All of the resultant shapefiles are in UTM coordinates associated with the aerial photograph mosaics.

Cross Section Surveys: Detailed measurements of channel properties and bed material characteristics were taken in a 1-km long reach centered around RK 283 (RM 176) to provide more detail on channel changes and to model thresholds for bed load transport. This particular segment of the Colorado River was chosen because conditions within the reach are relatively natural; the reach includes a through-flowing secondary channel, alluvial channel margins with a limited amount of rip-rap, and well-defined floodplains along both the north and south sides of the channel (Fig. 6). In addition the study reach includes property on the south bank that was obtained by the U.S. Fish and Wildlife Service and the Bureau of Reclamation, and it is therefore relatively easy to access.

Figure 6. Location of reach used for detailed studies of channel change.

Initial topographic surveys of the study reach were conducted in May, 1998. Eleven cross sections were placed at evenly spaced 80-meter intervals through the reach, covering a total channel length of 800 m. Measurements of the channel-bed and water-surface elevations were taken with a total station and a rubber raft outfitted with a depth sounder. Survey measurements of the cross sections were repeated in August, 1998; October, 1999; and July, 2001. Separate measurements of water surface elevations were taken periodically throughout the study for use in calibrating a one dimensional hydrodynamic model for computing roughness coefficients, velocities and boundary shear stresses for various flow levels (discussed below).

Samples of the bed sediment were taken at a number of locations within the study reach. The bed surface (armor layer) was sampled with point counts of 100 or 200 particles following the method described by *Wolman* [1954]. Particles were sampled randomly within specific areas of the channel, and measured at 1/2-phi intervals using a metal template (gravelometer). A separate sample of the subsurface sediment (substrate) was obtained in order to determine the size distribution of the bulk bed material. A total of 135 kg of sediment was collected in this sample, with the largest rock weighing 10 kg, or 7% of the total sample weight. The coarse fraction (>32 mm) of the subsurface sample was sieved in the field and the fine fraction (<32 mm) was sieved in the laboratory, again at 1/2-phi intervals. A graphical plot of the grain size distribution of this sample (Fig. 7) indicates that the substrate has a median grain size, D_{50s}, of 30 mm, and 17% is finer than sand (2 mm). The size distribution of this sample is very similar to two other samples collected previously in the 15-mile reach [*Pitlick et al.*, 1999].

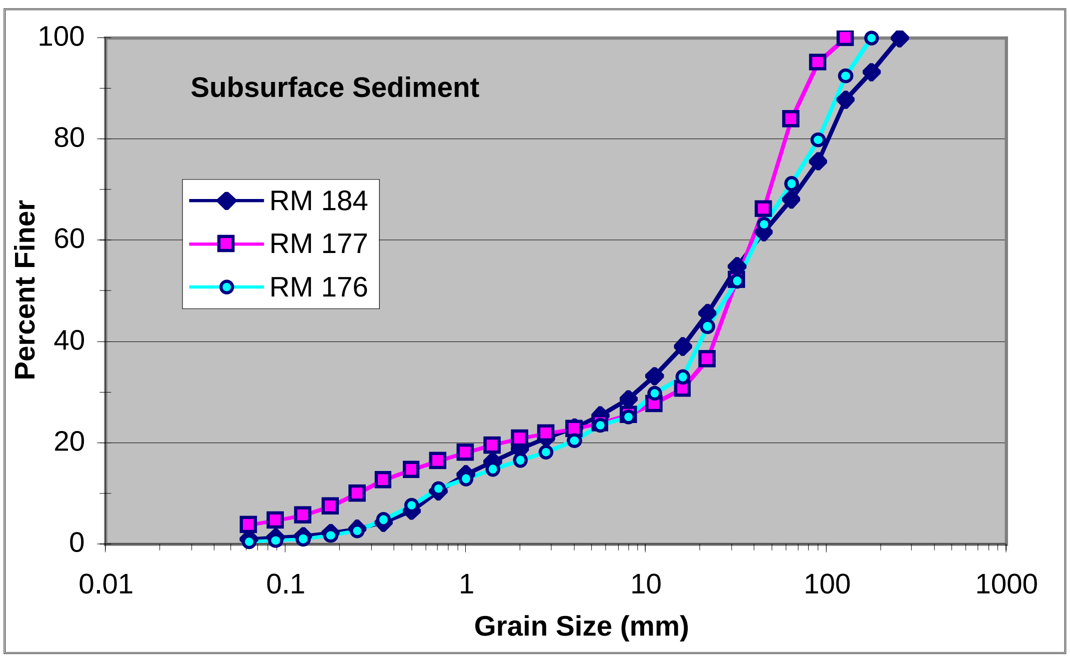


Figure 7. Grain size distributions of subsurface sediment at 3 locations in the 15-mile reach.

Additional characteristics of the study reach are summarized in Table 1. Based on data from the cross section surveys, the channel has an average bankfull width of 127 m, an average bankfull depth of 1.90 m; and an average median grain size of 69 mm (Table 1). These values correspond relatively closely to the average characteristics of the 15-mile reach, determined from earlier surveys of channel geometry [*Pitlick et al.*, 1999]. In comparison to the 15-mile reach as a whole, the site at RK 283 is characterized by a slightly lower bankfull depth and a slightly higher median grain size (Table 1). These differences are primarily the result of an increase in channel gradient within the study reach: the study reach has an average slope of 0.0020 m/m, whereas the 15-mile reach has an average slope of 0.00175 m/m.

Table 1. General characteristics of the Colorado River at the RK 283 (RM 176) study site.

	Bankfull Width (m)	Bankfull Depth (m)	Median Grain Size, D_{50} (mm)[1]
XSECT 1	132	1.38	60
XSECT 2	110	2.15	-
XSECT 3	116	1.69	52
XSECT 4	105	1.70	59
XSECT 5	87	2.20	99
XSECT 6	104	2.40	81
XSECT 7	119	1.96	82
XSECT 8	148	1.98	76
XSECT 9	154	1.82	-
XSECT 10	163	1.82	67
XSECT 11	163	1.80	-
Site average	127	1.90	69
15-mile reach average[2]	134	2.54	58

1. Values of D_{50} at cross sections 6, 7, 8, and 10, represent the average of two samples.
2. Averages for the 15-mile reach from *Pitlick et al.* (1999).

Sediment Transport

Sand and Fine Gravel: Seasonal transport of sand and fine gravel over bars and riffles was monitored by installing a series of stream-bed sediment traps at various locations. The traps consist of 20-cm diameter coffee cans mounted within a piece of plastic pipe, both placed vertically and flush with the bed surface (Fig. 8). The cans were filled with clean gravel > 32 mm in size. At various times after the peak in the annual hydrograph the cans were retrieved, emptied of fine sediment, refilled with clean gravel and placed back in the bed. In general it was not possible to retrieve the cans in flows more than ~0.5 m deep. Sediment samples taken from the traps were subsequently sieved at 1/2 phi intervals.

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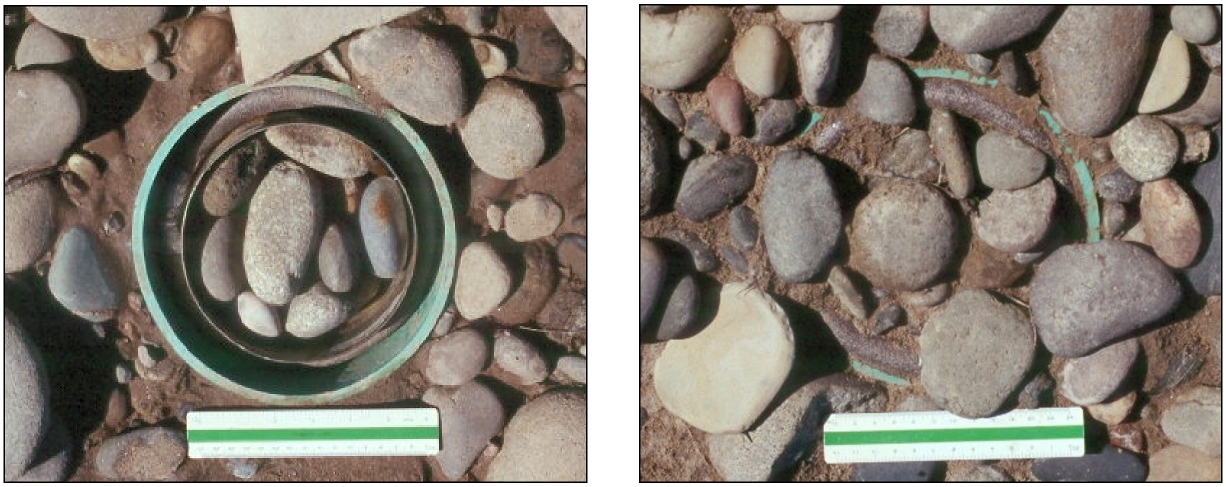


Figure 8. Traps used to monitor the movement of sand. Photo on the left (a) shows a trap prior to runoff; photo on right (b) shows the same trap after runoff. Ruler is 17 cm in length.

<u>Cobble and Gravel</u>: Estimates of discharges required to mobilize cobble- and gravel-sized sediment were made by coupling several equations for flow and sediment transport, calibrated with the aid of field data from the study reach near RK 283. Spot measurements of water-surface elevations were made at each of the cross sections in the study reach at eight different discharges ranging from 37 to 394 m^3/s (1300-13900 ft^3/s). The water-surface measurements were used with cross section data to calibrate a one-dimensional hydraulic model to determine variations in flow properties, including channel roughness (Manning's n), mean velocity, U, and average boundary shear stress, τ. Other measures of flow conditions, such as wetted perimeter, P, and water surface area, A_s, were obtained as part of this process.

Thresholds for motion of cobble- and gravel-sized sediment (framework grains) were estimated from the relation for dimensionless shear stress:

$$\tau^* = \frac{\tau}{(\rho_s - \rho)\, g\, D} \qquad (1)$$

where ρ_s and ρ are the densities of sediment and water, respectively, g is the gravitational acceleration, and D_{50} is the median grain size of the bed surface (armor layer). In a simple physical sense, the variable τ^* represents a balance between the fluid forces acting to move particles on the bed versus the resistance due to their mass. Movement of a small number of framework grains begins when τ^* exceeds a threshold or critical value, τ^*_c. Results from field and laboratory studies suggest that values of τ^*_c may be affected by several factors, including particle shape [*Gomez*, 1994], sand content [*Wilcock*, 1998], spatial variations in bed texture [*Lisle et al*., 2000; *Konrad et al*., 2002; *Church et al*., 1998], and variations in relative roughness and average channel gradient [*Mueller et al., 2005*]. In addition, there is a practical problem of defining the onset of motion or the degree of bed mobilization, i.e. whether bed load transport involves only a few of the coarse clasts or many clasts. Finally, some gravel-bed rivers can carry significant amounts of sand-sized sediment; this presents a potential problem because sand moves at flows much lower than those required to move the coarser framework grains, plus sand can move either as bed load or suspended load, depending on the flow level and local shear stress. Such is the case in the Colorado River. Thus, it is possible to distinguish three separate phases of bed load transport: the first phase, involving movement of sand and fine gravel over an otherwise stable bed surface, is termed *overpassing* (*Ashworth and Ferguson*, 1989); the sediment moved in this phase is not the same as 'wash load' (the sediment supplied from sources other than the bed itself), and in fact may represent a significant proportion (> 20 %) of the total annual bed load carried by a gravel river (this point is pursued in detail later). The second transport phase, involving sporadic motion of small to moderate percentages of the framework grains, is termed *partial transport* [*Wilcock and McArdell*, 1993]. A recent analysis of bed load transport thresholds by *Mueller et al.* (2005) indicates that partial transport begins at flows equal to about 67% of the bankfull discharge. The third bed load transport phase, involving motion of most all particles on the river bed is termed *fully mobilized transport*[*Wilcock and McArdell*, 1993]. This transport phase has been equated with the bankfull discharge [*Pitlick et al*., 1999; *Pitlick and Cress*, 2000; *Pitlick and Wilcock*, 2001], the rationale being that these flows shape the channel and thereby mobilize most all of the sediment forming the channel boundary.

The flow levels or discharges required to reach the transport phases discussed above are determined by selecting a threshold value of τ^* and solving (1) for the corresponding shear stress, τ. In previous studies of the Colorado River and the Gunnison River, *Pitlick et al*. [1999] set the threshold for initial motion at $\tau^* = 0.03$. Results from field studies elsewhere served as the basis for selecting that value; however, the value of 0.03 is not a hard number, and recent work suggests that there may be substantial variation in the critical τ^* due to sediment sorting, imbrication, and the sand-content of the bed surface layer. Indeed, this study was motivated in part by uncertainties associated with the choice of the critical τ^*. For the purposes of the present study, the threshold for initial motion was determined using an empirical relation developed by *Mueller et al*. [2005]. This relation is based on an analysis of flow and bed load transport measurements taken in 45 gravel-bed streams and rivers throughout the western USA and Canada. The analysis focused on variations in the threshold for bed load transport which arise from changes in flow structure as the average channel gradient and bed roughness increase. For each of the data sets, *Mueller et al.* [2005] plotted the relation between bed load transport rate and dimensionless shear stress, and, following the procedure of *Parker et al.* [1982], estimated the reference dimensionless shear stress, τ^*_r, associated with a small, non-zero bed load transport rate. The resulting estimates of τ^*_r were then correlated to the reach-average channel slope, giving the values shown in Figure 9. A least squares fit of the data in this figure gives the following equation:

$$\tau^*_r = 2.18S + 0.021 \qquad (2)$$

where S is the average channel gradient. This relation is statistically significant ($r^2 = 0.70$ and $p \ll 0.001$), and indicates that τ^*_r increases linearly with increasing channel gradient. This result is counterintuitive, but explained by hydrodynamic effects associated with poorer sorting and high roughness of the bed material in high-gradient channels. The monitoring site near RK 283 has an average gradient of $S \approx 0.0020$, thus the estimated τ^*_c for that location is 0.025.

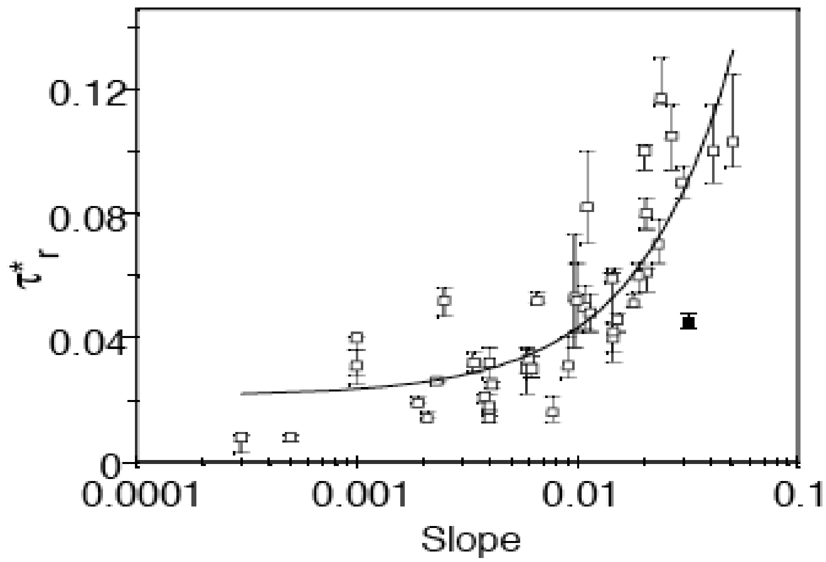


Figure 9. Variation in τ^*_r as function of slope with error bars indicating potential range of τ^*_r values for individual data sets. A logarithmic scale is used for the x-axis to highlight the range in values for moderate-high slopes. One outlier (solid symbol) was excluded from the analysis (from *Mueller et al.*, 2005).

The shear stress available to move sediment on the channel bed varies temporally as the discharge rises and falls, and spatially as the flow accelerates or decelerates over the topography (pools and riffles). The boundary shear stress, τ, is the force per unit bed area acting in the direction of flow,

$$\tau = \rho\, g\, R\, S_e \qquad (3)$$

where ρ is the density of water, g is the gravitational acceleration, R is the hydraulic radius, and S_e is the slope of the energy grade line, also termed the friction slope. In channels with a high width-depth ratio, R is approximately equal to the mean flow depth, h, hence these variables are often used in place of each other. Assuming ρ and g are constant, (3) shows that τ varies with the product of R and S_e . Both R and S_e may vary with discharge, however, not necessarily in the same direction. As discharge increases, R generally increases; however, S_e may increase, decrease, or stay essentially the same, depending on the topography and sinuosity of the channel reach. Changes in channel width and/or bed level caused by pools and riffles force the water to accelerate (or decelerate), adding to the fluid force produced solely by the weight of the water moving downstream. The effects of these flow accelerations can be accounted for using the one-dimensional equation for gradually varied flow, which can be written as follows,

$$S_e = -\frac{dH}{dx} = -\frac{d}{dx}\left(z + h + \frac{U^2}{2g}\right) \tag{4}$$

where S_e is the streamwise energy gradient (also termed the friction slope), H is the total energy, z is the average bed elevation, h is the average flow depth (approximately equal to the hydraulic radius, R), and $u^2/2g$ is the velocity head. The first term on the right hand size of (4), dz/dx, is the bed surface slope, which may be either positive or negative. The second term, dh/dx, is the water surface slope, which also can be either positive or negative. These two terms are typically of the same magnitude, thus they are both important; however, they can be of opposite sign, in which case their effects on the friction slope and shear stress can offset each other. Together, the first two terms, dz/dx and dh/dx, represent the streamwise gradient in gravitational potential energy. The third term, $d(u^2/2g)/dx$, represents the streamwise gradient in kinetic energy, which is produced by changes in the speed of the water as it flows over the topography; this term is generally smaller than the other two, however it can add significantly to the total energy loss, particularly in cases where the two other terms are of equal magnitude but opposite sign. Equation 4 thus shows that the flow's ability to do work against the bed friction, dH/dx, depends on the sum of three different terms, which vary in their importance depending on the particular flow level and site characteristics.

Equation 4 was solved using the standard step method [*Henderson*, 1966], an iterative procedure that balances the total energy, H, along a series of channel cross sections. The model was used to predict the depth and velocity at each cross section for a series of known discharges and assumed values of the roughness coefficient, Manning's n. The model results and assumed values of Manning's n were then verified by comparing the predicted water surface elevations with those measured in the field.

RESULTS

Summary of Streamflows, 1998-2004

This study coincided with a period of sustained and severe drought that affected most of the upper Colorado River basin. Hydrologists continue to discuss the significance and long-term context of this drought, however, it appears that water years 2002-2004 were the lowest in the upper Colorado River basin in at least 100 years (*USGS Fact Sheet 2004-3062, August, 2004*). The 7-year period of this study includes two extremely dry years (2002 and 2004) and three other below-average years, 2000, 2001, and 2003 (Table 2). The 2002 water year stands out as the most extreme of these. In 2002 the peak discharge of the Colorado River near Cameo was only 121 m^3/s (4260 ft^3/s) (Table 2); this flow ranks as the lowest instantaneous peak discharge in the 71-year period of record for this gauge. The peak discharge of the Gunnison River at the Whitewater gauge was only 82 m^3/s (2890 ft^3/s) (Table 2). This flow occurred in September, thus it was not associated with snowmelt; it ranks as the second lowest peak in the 96-year period of record for this gauge. The 2004 peaks rank as the third and fourth lowest values at the Cameo and Whitewater gauges, respectively.

Table 2. Summary of streamflows for the period 1998-2004, and comparisons with long-term averages at gauging stations on the Colorado River and Gunnison River.

COLORADO RIVER NR CAMEO, CO, USGS 09095500

	Peak Discharge (ft^3/s)	Peak Discharge (m^3/s)	Percent of Average	Annual Discharge (ft^3/s)	Annual Discharge (m^3/s)	Percent of Average	Annual Runoff (ac-ft)
ave 1950-97	18520	**524**		3850	**109**		
1998	15700	445	85	4230	120	110	3063000
1999	15600	442	84	3820	108	99	2766000
2000	16400	464	89	3210	91	83	2324000
2001	9720	275	52	2680	76	70	1940000
2002	4260	121	23	1750	50	45	1267000
2003	21000	595	113	2650	75	69	1919000
2004	7450	211	40	2270	64	59	1643000

COLORADO RIVER NR PALISADE, CO, USGS 09106150

	Peak Discharge (ft^3/s)	Peak Discharge (m^3/s)	Percent of Average	Annual Discharge (ft^3/s)	Annual Discharge (m^3/s)	Percent of Average	Annual Runoff (ac-ft)
ave 1991-97	20240	**573**		3420	**97**		
1998	14800	419	73	3680	104	107	2664000
1999	13300	377	66	3060	87	89	2215000
2000	14400	408	71	2470	70	72	1788000
2001	8010	227	40	1780	50	52	1289000
2002	4520	128	22	940	27	27	681000
2003	21500	609	106	1970	56	58	1426000
2004	5970	169	29	1480	42	43	1072000

Table 2, continued

GUNNISON RIVER NR GRAND JUNCTION, CO, USGS 09152500

	Peak Discharge (ft^3/s)	Peak Discharge (m^3/s)	Percent of Average	Annual Discharge (ft^3/s)	Annual Discharge (m^3/s)	Percent of Average	Annual Runoff (ac-ft)
ave 1950-97	10800	**306**		2470	**70**		
1998	10600	300	98	2890	82	117	2092000
1999	6430	182	60	2340	66	95	1694000
2000	5770	163	53	2020	57	82	1462000
2001	5170	146	48	1620	46	66	1173000
2002	2890	82	27	1110	31	45	804000
2003	5990	170	55	1190	34	48	862000
2004	3790	107	35	1220	35	49	883000

COLORADO RIVER NR CO-UT STATE LINE, USGS 09163500

	Peak Discharge (ft^3/s)	Peak Discharge (m^3/s)	Percent of Average	Annual Discharge (ft^3/s)	Annual Discharge (m^3/s)	Percent of Average	Annual Runoff (ac-ft)
ave 1951-97	28140	**797**		6360	**180**		
1998	26100	739	93	7390	209	116	5350000
1999	17900	507	64	6020	170	95	4358000
2000	17900	507	64	4820	137	76	3490000
2001	13200	374	47	3870	110	61	2802000
2002	5520	156	20	2420	69	38	1752000
2003	26100	739	93	3640	103	57	2635000
2004	9450	268	34	3350	95	53	2425000

The period from 1998-2004 was not only dry overall, but also characterized by an unusual string of years starting in 1998 in which one year after another was followed by lower and lower peak discharges and lower annual runoff. Figure 10 shows trends in annual runoff at the two gauges immediately upstream of the 15-mile reach, Colorado River near Palisade and Colorado River near Cameo, respectively. The record for the Palisade gauge is relatively short (14 yr), thus not particularly useful for assessing recent hydrologic trends. The record from this gauge suggests that prior to 1998 annual runoff was equally divided between above-average and below-average years (Fig. 10a). The record for the Cameo gauge, which extends back to the early 1930s (Fig. 10b), shows that the sequence of low-flow years from 1998 to 2004 was unusual in comparison to any equivalent period prior to 1950. However, since 1950, there have been at least two other strings of dry years. From 1954-1969, for example, the average annual discharge at Cameo was exceeded in only four years, or half the expected number. The period from 1987 through 1992 is likewise characterized by a series of below-average water years. The 2000-2004 drought was the most severe of these low-flow periods, and it should be a cause for concern if strings of low-flow years occur more often in the future, whether due to planned depletions or changes in climate.

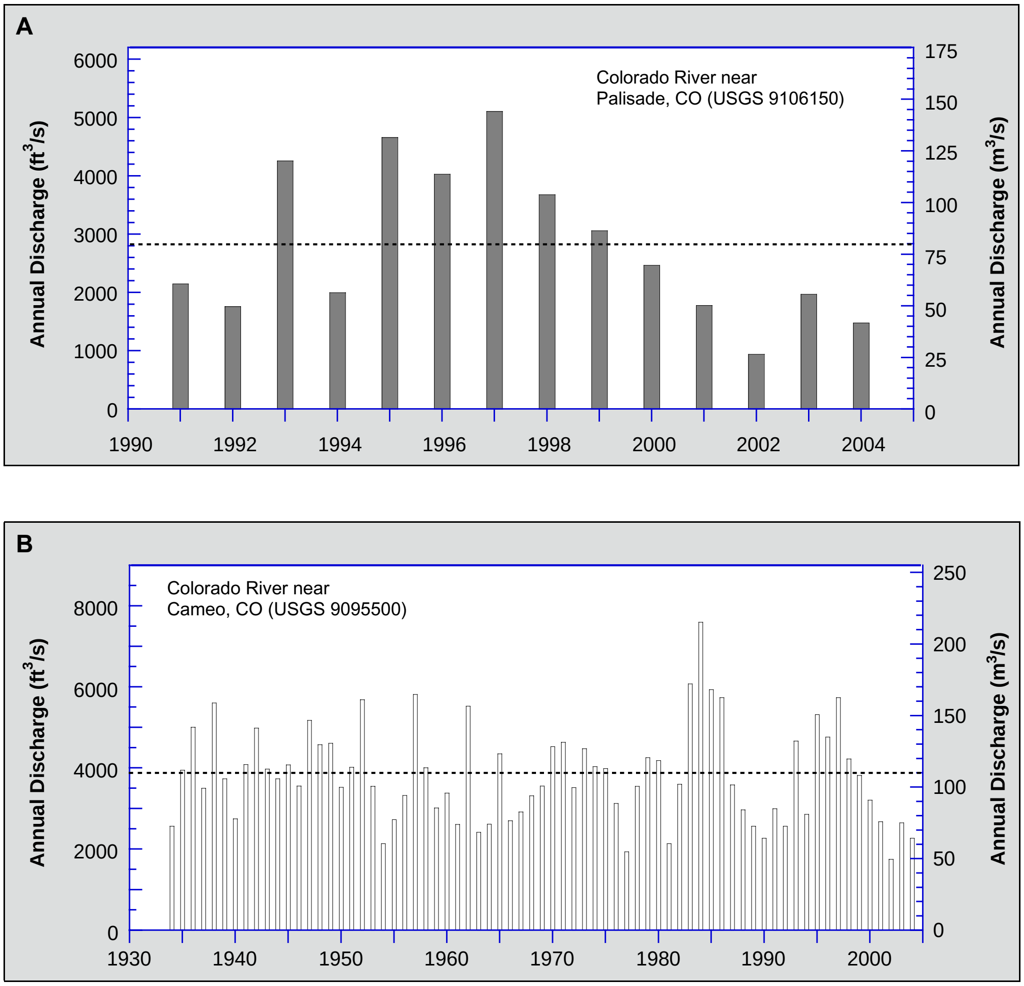


Figure 10. Trends in annual runoff of the Colorado River based on streamflow records from USGS gauging stations (a) near Palisade, CO, and (b) near Cameo, Colorado. The dashed line indicates the average annual discharge for the period of record.

The flow recommendations provided in our previous reports (*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000) focused on physical processes of sediment transport, under the assumption that these processes are important for maintaining habitats used by the native fishes and other aquatic organisms. The previous recommendations targeted two separate stages of bed-load transport: (i) initial motion, corresponding to flows equal to approximately 1/2 the bankfull discharge, and (ii) complete mobilization, corresponding to flows equal to the bankfull discharge. Table 3 lists specific values of these discharges for the 15- and 18-mile reaches, along with the recommended durations of these discharges (days per year), and the number of days/year that those discharges were observed during the period 1998-2004. These results provide an indication of the ability of the Recovery Program to meet the flow recommendations given in previous studies and reports. The data listed in Table 3 indicate that the target flows for initial motion of the bed sediment (~1/2 the bankfull discharge) were not exceeded very often over the duration of the study period-only about 1/3 of the recommended frequency. The target flows for complete mobilization of the bed (the bankfull discharge) were not exceeded in any year. The flows observed during the study period, 1998-2004, thus fall far short of the recommendations given previously.

Table 3. Comparison between recommended and observed frequencies of sediment-transporting flows in the 15-mile and 18-mile reaches, 1998-2004. Threshold discharges and recommended frequencies are based on results presented in *Pitlick and Cress* (2000).

	15-Mile Reach		**18-Mile Reach**	
Threshold flows:	Q_c = 9800 ft^3/s (278 m^3/s)	Q_b = 21500 ft^3/s (608 m^3/s)	Q_c = 19400 ft^3/s (548 m^3/s)	Q_b = 34600 ft^3/s (979 m^3/s)
Recommended Frequency (days/yr)	30	5	30	5
Observed Frequency (days/yr)				
1998	24	0	13	0
1999	31	0	0	0
2000	10	0	0	0
2001	0	0	0	0
2002	0	0	0	0
2003	13	0	6	0
2004	0	0	0	0
Average Frequency (days/yr)	11	0	< 3	0

Coordinated Reservoir Operations (CROPS)

Peak snow-water equivalents and reservoir levels in the Colorado River basin were sufficient in the first two years of this study- 1998 and 1999- to allow a portion of the runoff to bypass upper basin reservoirs, and thus enhance flows in the 15-mile reach (coordinated reservoir operations were also implemented in 1997, before this study was initiated). Plans were in place to bypass flows in 2000, however, warm spring weather rapidly depleted the snowpack, and bypass operations were called off.

Coordinated reservoir operations were implemented for 7 days in 1998, providing an additional 24,000 acre-feet of runoff to the 15-mile reach. The upper panel in Figure 11 shows that these releases increased peak daily discharges at Palisade by about 60 m^3/s (~2,100 ft^3/s), and extended the duration of peak runoff by several days. In 1999, coordinated reservoir operations were implemented for 10 days (lower panel, Fig. 11), providing an additional 40,000 acre-feet of runoff to the 15-mile reach. These releases increased peak daily discharges at Palisade by about 70 m^3/s (~2,500 ft^3/s).

Colorado River below Grand Valley Diversion near Palisade, CO

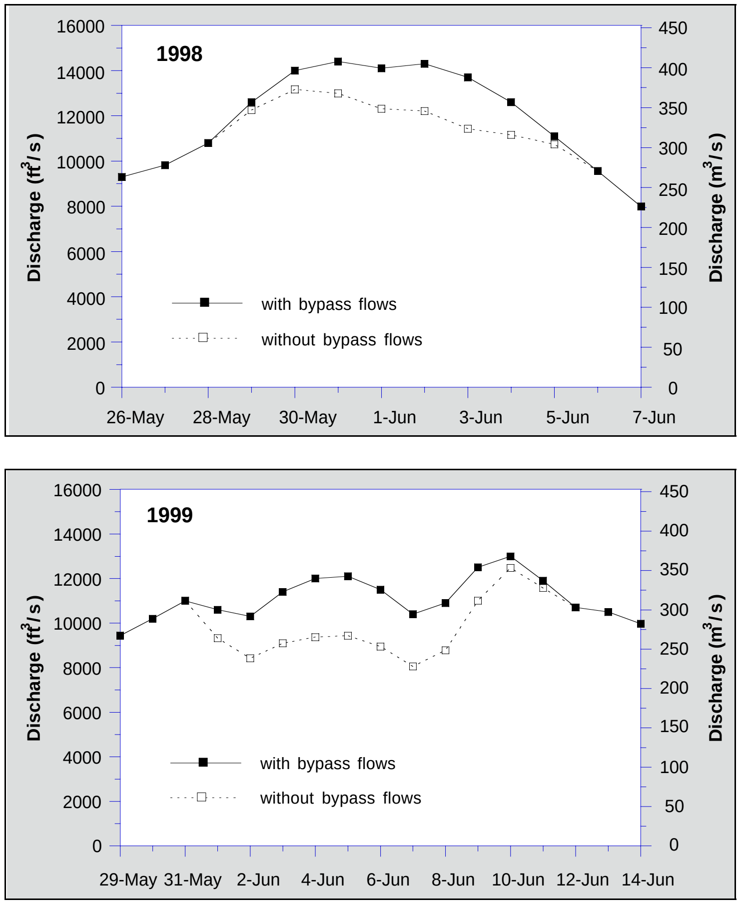


Figure 11. Daily discharge during the periods of peak snowmelt runoff in 1998 and 1999, Colorado River, below Grand Valley diversion, near Palisade, Colorado. Dotted lines indicate discharges that would have occurred without coordinated reservoir operations.

The principal hydrologic effect of coordinated reservoir operations was to increase streamflows in the 15-mile reach by 10-20%. In 1998 and 1999, this was just enough to push discharges above the threshold for initial motion. This is an important result because periodic movement of the bed material is critical for maintaining habitats within the 15- and 18-mile reaches [*Pitlick and Van Steeter*, 1998; *Osmundson et al*., 2002]. It is very likely that these flows increased the proportion of coarse clasts entrained from the bed. However, we know from observations in subsequent years, and observations on other gravel-bed rivers, that at these flows (about 1/2 the bankfull discharge), very limited portions of the bed are reworked, and transport is restricted to the smallest grain sizes; very few cobble-sized particles are entrained and transported at these flows [*Wilcock et al*., 1996; *Lisle et al*., 2000; *Konrad et al*., 2002]. Given the size and scale of the Colorado River, it is unlikely that 10-20% increases in discharge <u>at these flow levels</u> will produce much visible change in the geomorphology of the channel. The characteristics of the channel bed, such as benthic algae biomass and the presence/absence of interstitial fines, are almost certainly affected to some extent, but our ability to quantify the importance of these characteristics during periods of high flow is very limited. Having said that, there is a clear rationale for continuing and expanding the use of coordinated reservoir operations, primarily to maintain the mass balance of sediment supplied to the 15- and 18-mile reaches. In most rivers, sediment transport rates increase nonlinearly with discharge, thus small increments in flow can increase the efficiency of transport significantly. This comment applies to both fine and coarse sediment. Measurements of suspended sediment loads at Cameo, for example, indicate that with a 20% increase in discharge there is a 50% increase in the suspended sediment load the Colorado River (the dynamics of fine sediment are discussed in more detail later). The effect on bed load is likely to be even greater, given what we know from measurements on other similar-sized rivers. The figure below shows a photograph of the Selway River, a large gravel-bed river in central Idaho, and an accompanying set of measurements showing the relation between water discharge and bed load transport rate. Although the Selway River is located in a much different setting than the Colorado River, the characteristics of the two rivers are quite similar in terms of average gradient, bed material grain size, channel width and bankfull discharge.

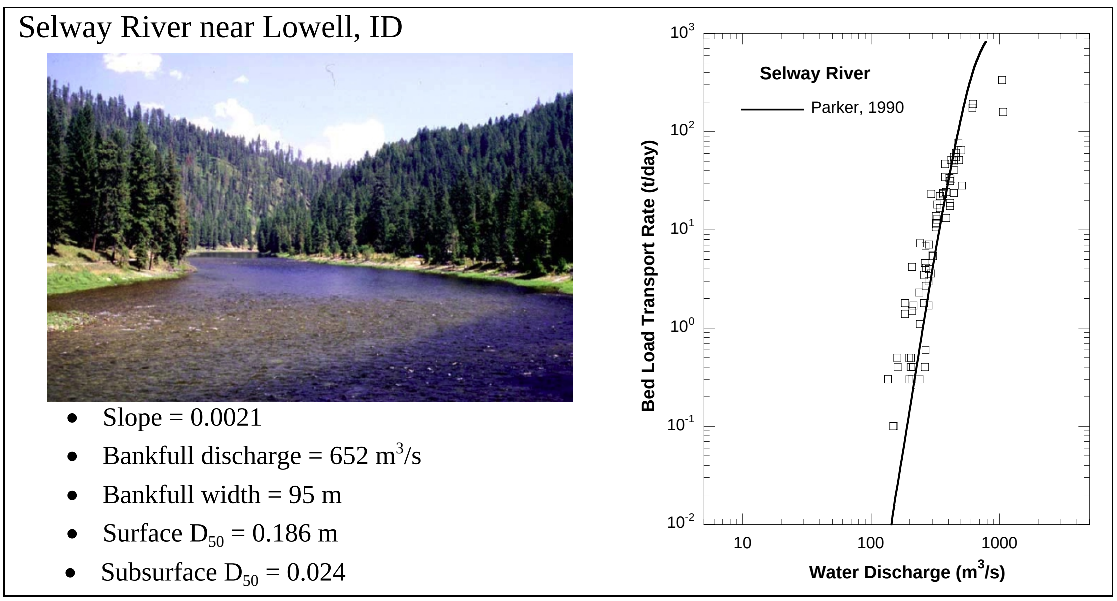


Figure 12. Photograph and bed load transport relation for the Selway River near Lowell, ID, a river with characteristics similar to the Colorado River (source: *King et al.*, 2004)

The bed load measurements on the Selway River are of exceptionally high quality: the data exhibit relatively low scatter, and form a steep relation between bed load transport rate and discharge, $Q_b = 3.85E\text{-}12\ Q^{4.92}$. In addition, the data closely match the empirical bed load transport relation of *Parker* [1990], which could be used as the basis for modeling transport under different flow conditions. The bed load measurements on the Selway River are perhaps not directly applicable to the Colorado River, however, they illustrate the important point that once the threshold for bed load transport is exceeded transport rates increase very rapidly. If, for example, the discharge on the Selway River increases by just 20% from 300 to 360 m^3/s the transport rates will increase from about 6 ton/day to 15 ton/day, a difference of 150%. This represents a large change in bed load transport for a small change in discharge. However, if we were in the field, we would probably not be able to detect much difference in the channel from one flow to the next. Rivers can carry substantial volumes of sediment without undergoing much visible change, as long as the flows needed to carry the sediment can balance the load supplied from upstream. One of the goals of coordinated reservoir operations, therefore, should be to maintain the mass balance of sediment through the 15- and 18-mile reaches, and it follows from the arguments presented above that modest changes in discharge can increase the efficiency of bed load and suspended load transport substantially.

The reservoir operators and federal agencies involved in scheduling bypass flows set an important precedent in demonstrating that they could coordinate efforts to enhance flows to improve in-channel habitats in the 15-mile reach. The bypass flows were successful in boosting background flows in a specific window of time, making it more likely that there was localized movement of gravel- and cobble-sized sediment in the 15- and 18-mile reaches. Without the bypass flows bed load transport in the period of observation would have been more limited than it was, and vegetation would have become established in the active channel sooner than was observed. The volumes of water released in 1998 and 1999 were, however, a small fraction of the total runoff of the Colorado River in those years (Fig. 13). When plotted this way, it seems evident that the flow added by coordinated reservoir operations will need to be increased before we can expect to see measurable changes in the morphology or habitat characteristics of the 15-mile reach. The concepts of sediment transport referred to above imply that modest changes in discharge lead to substantial changes in transport rates, thus if coordinated reservoir operations can be continued over a period of several years- not just three- the effects of increased transport frequency should carry over to habitat characteristics.

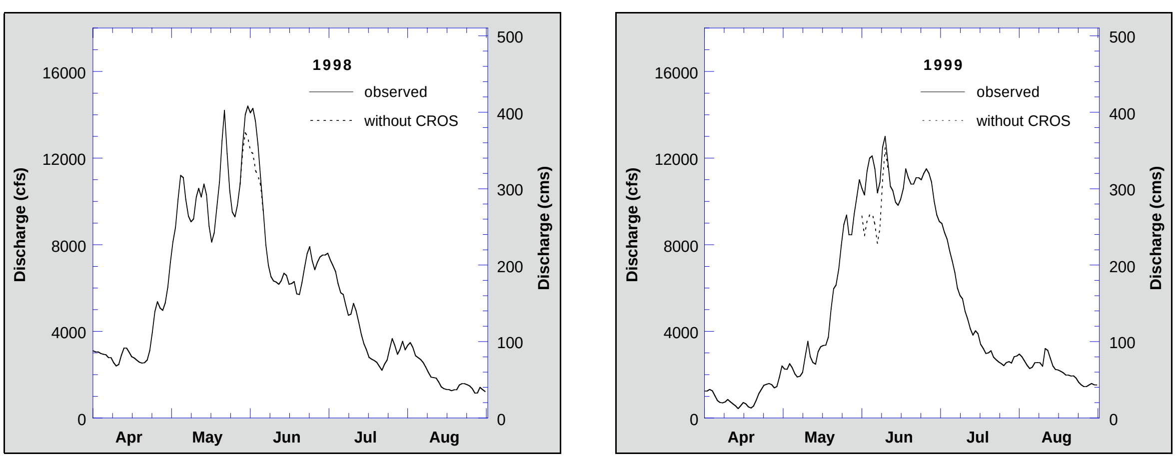


Figure 13. Daily discharges for the period of snowmelt runoff in 1998 and 1999, Colorado River below Grand Valley diversion, near Palisade, Colorado, USGS gauge 09106150.

The geomorphic effects and benefits of coordinated reservoir operations will likely become more evident if the volume and duration of releases can be increased substantially. To envision the difference larger contributions might make, Figure 14 compares spring-summer hydrographs of the Colorado River for several years corresponding to pre-and post-management time periods (before and after 1950). The panel on the left compares two years of below-average runoff, and the panel on the right compares two years of above-average runoff. In each pair of years, the annual runoff was roughly the same, as was the timing of the peak discharge. The principal difference, reflecting the operation of upper basin reservoirs, is the lower magnitude of the more-recent peaks. The question is: What would it take to make up the difference in peaks in these years? In the first case, 1994, it would require an additional 100,000 acre-ft of water, spread out over about 15 days, to match the magnitude and duration of the 1940 peak. In the second case, 1993, it would require an additional 150,000 acre-ft of water, spread out over 22 days, to match the magnitude and duration of the 1948 peak. These are large volumes of water, and probably well beyond present operational capabilities. The point of these comparisons is not to offer new flow recommendations, or to argue that the Recovery Program should try to match pre-management hydrographs, but rather to suggest that the goals of coordinated reservoir operations should be to increase flows by more than 10-20%, and to extend the duration of high flows by more than several days. The Recovery Program should continue to pursue the recommendation given in the Phase 2 Report of the Coordinated Facilities Operation Study [*CWCB*, 2003] to augment spring flows by another 20,000 acre-ft, in addition to maximizing releases provided by coordinated reservoir operations. The rationale for increasing the magnitude and duration of the peak is to keep pace with the sediment supply from unregulated tributaries, which does not appear to have changed substantially in the period since 1950 when most of the upper basin reservoirs went on line [*Pitlick et al*. 1999; *Pitlick and Cress*, 2000].

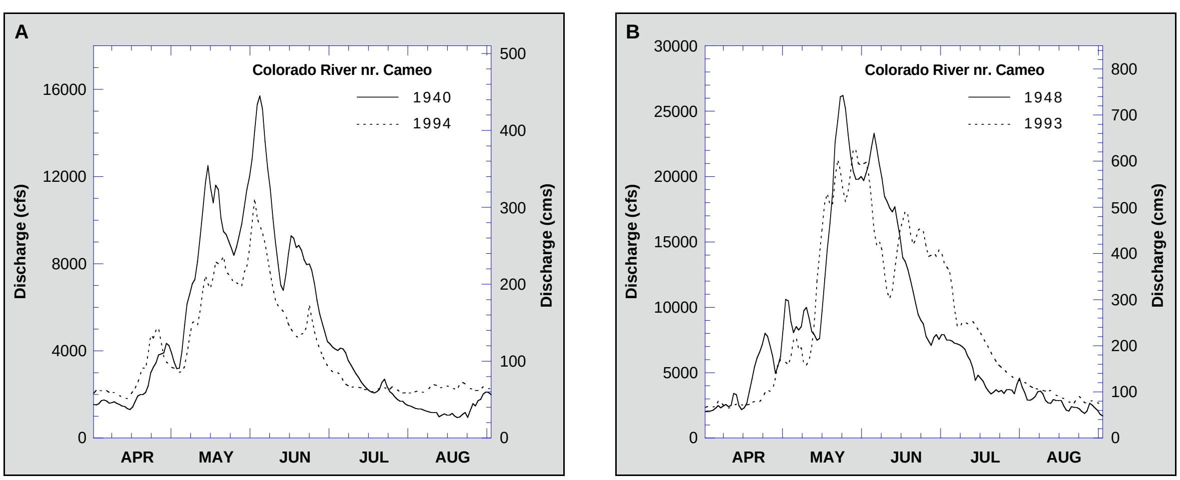
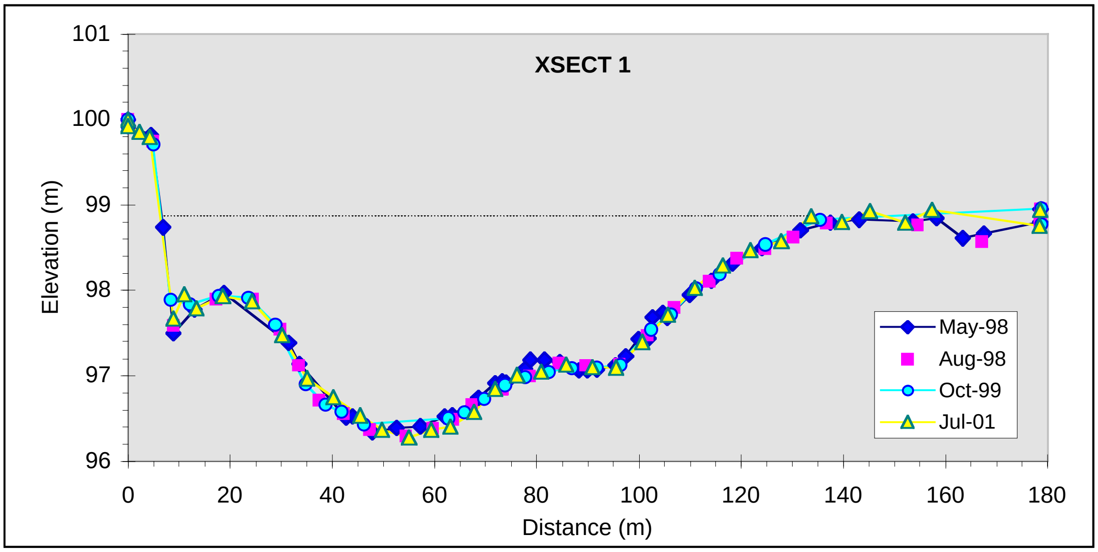


Figure 14. Comparisons of spring-summer hydrographs of the Colorado River near Cameo, CO, for years representative of pre- and current-management conditions; (a) compares two years of below-average runoff and (b) compares two years of above-average runoff. In each pair of years the total annual runoff was approximately the same, as was the date of the peak.

Changes in Channel Morphology

<u>Cross-section Measurements</u>: Survey measurements of the 11 main-channel cross sections in the reach near RK 283 (RM 176) show that changes in the overall morphology of the Colorado River were relatively minor during the monitoring period (Fig. 15). Minor amounts of bank erosion (< 2 m) occurred at several of the cross sections, but the topography of the study reach remained essentially unchanged. Enlarged views of the secondary channel that runs along the south (river left) side of the study reach show that minor amounts of sediment were deposited along the right bank (Fig. 16); however, overall, the topography of the secondary channel changed little during the monitoring period.



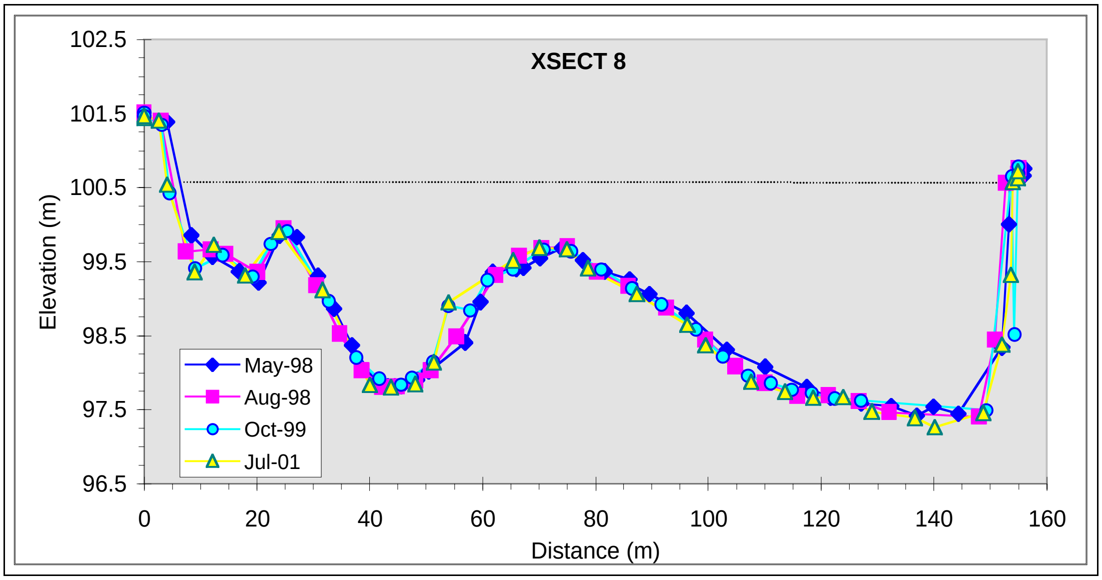


Figure 15. Main channel cross sections of the Colorado River near RK 283 (RM 176). Dashed line indicates the bankfull flow level.

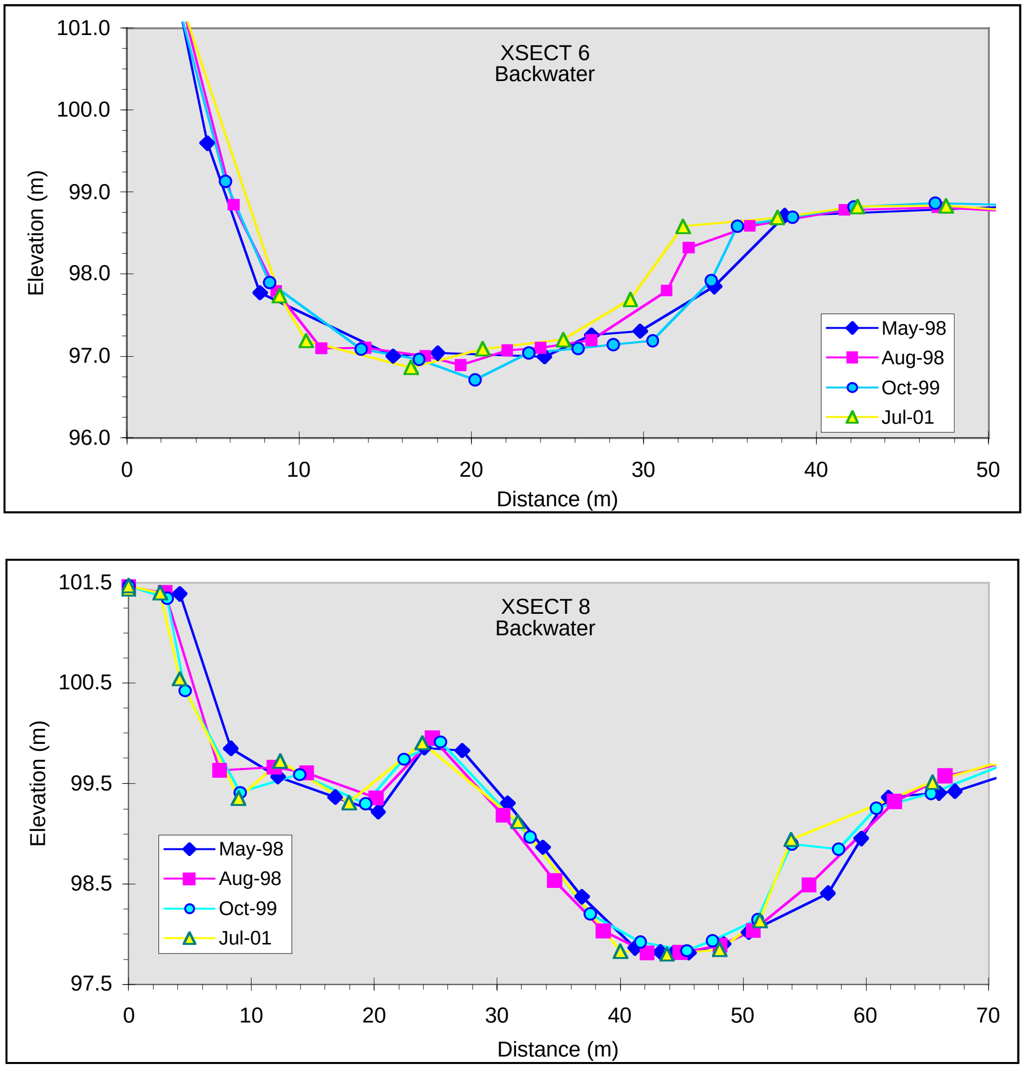


Figure 16. Detailed views of the secondary channel in the RK 283 study reach.

Scour and fill were monitored at three other secondary channels in the 15- and 18-mile reaches. One of these sites is located several hundred meters downstream of the reach discussed above, at RK 282 (RM 175.5). Two other sites are located in the 18-mile reach, one at RK 261, the other at RK 257 (RM 162 and 160, respectively); these sites were first surveyed in 1993 as part of an earlier study (*Pitlick et al*., 1999). The secondary channel at RK 282 is short and moderately sinuous, whereas the other two secondaries are relatively long and straight. Figure 17a shows that a substantial amount of sediment was deposited in the secondary at RK 282 in the first two years of monitoring; subsequently, in 2002, the mouth of the secondary was dammed by beavers, blocking flow to the main channel. Sedimentation in the other secondary channels was minor in comparison. The secondary at RK 261 aggraded by 0.2 to 0.5 m between 1995 and 2001 (Fig. 17b), but otherwise remained open to the main channel. The secondary channel near RK 257 changed very little, except for deposition of a small berm along the right bank (Fig. 17c).

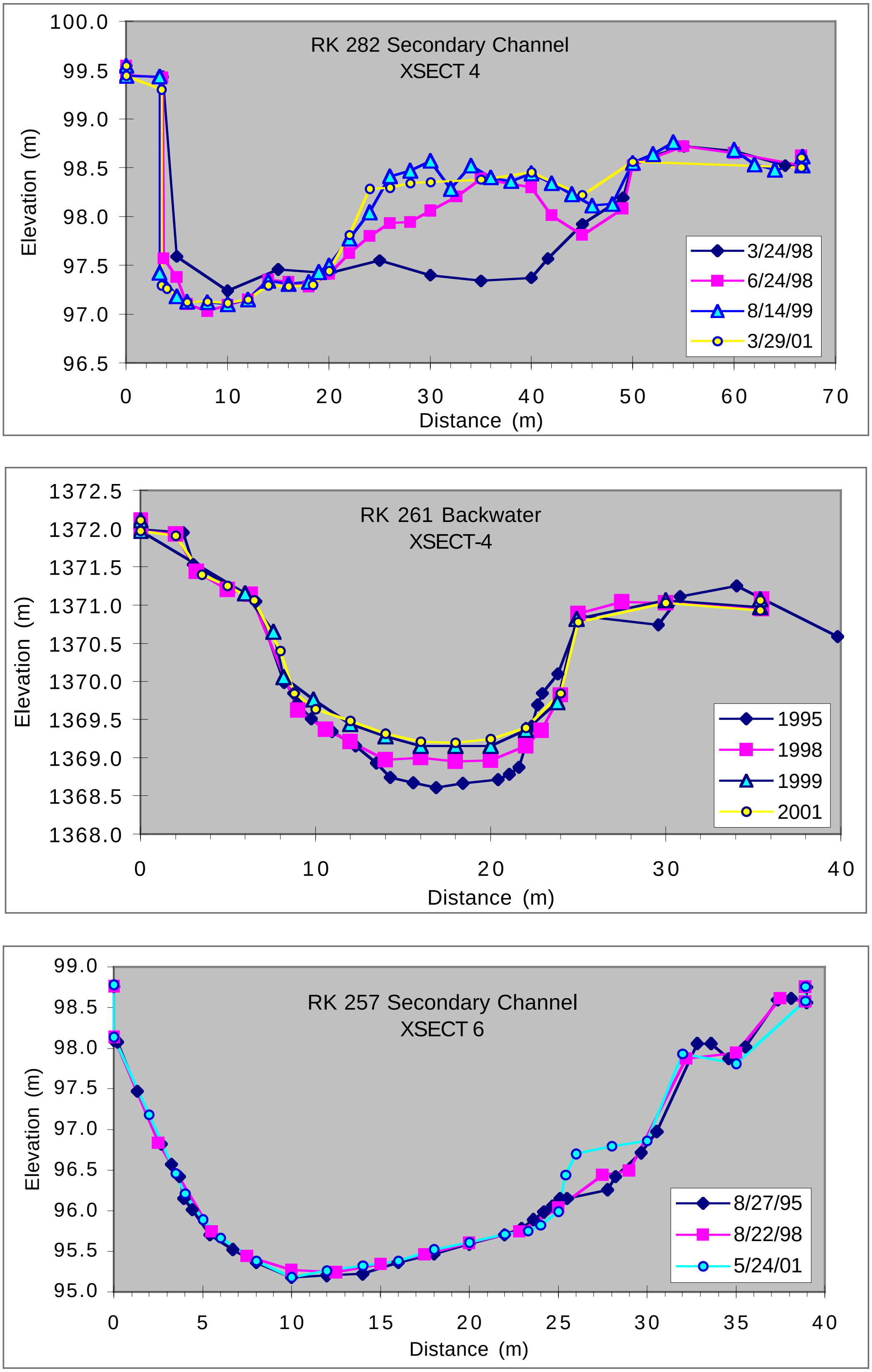


Figure 17. Cross sections of secondary channels/backwaters in the 15- and 18-mile reaches.

Comparison of Aerial Photographs: The analysis of aerial photographs suggests that locally there were some changes in the planimetric area of individual features from 1993-2000. Among the mapping units, it appears that bar area increased, side-channel area decreased, and main-channel area remained about the same (Fig. 18). It is important to note, however, that much of the change in bar and side-channel area occurred in the 18-mile reach, where flows were lower at the time of the photography in 2000 versus 1993. Flows levels in the 15-mile reach (RK 275-298) were similar in 2000 and 1993, thus changes there are real. The measurements show that side channels were abandoned near RK 295 and RK 279, and there was an increase in bar area and channel complexity at RK 282 (Fig. 18a). Overall, it appears that losses in side-channel area were offset by gains in bar area, thus it does not appear that the channel became much less complex between 1993 and 2000. Whatever the case, the changes measured during this period were small in comparison to changes measured over longer time periods (*Pitlick et al.*, 1999).

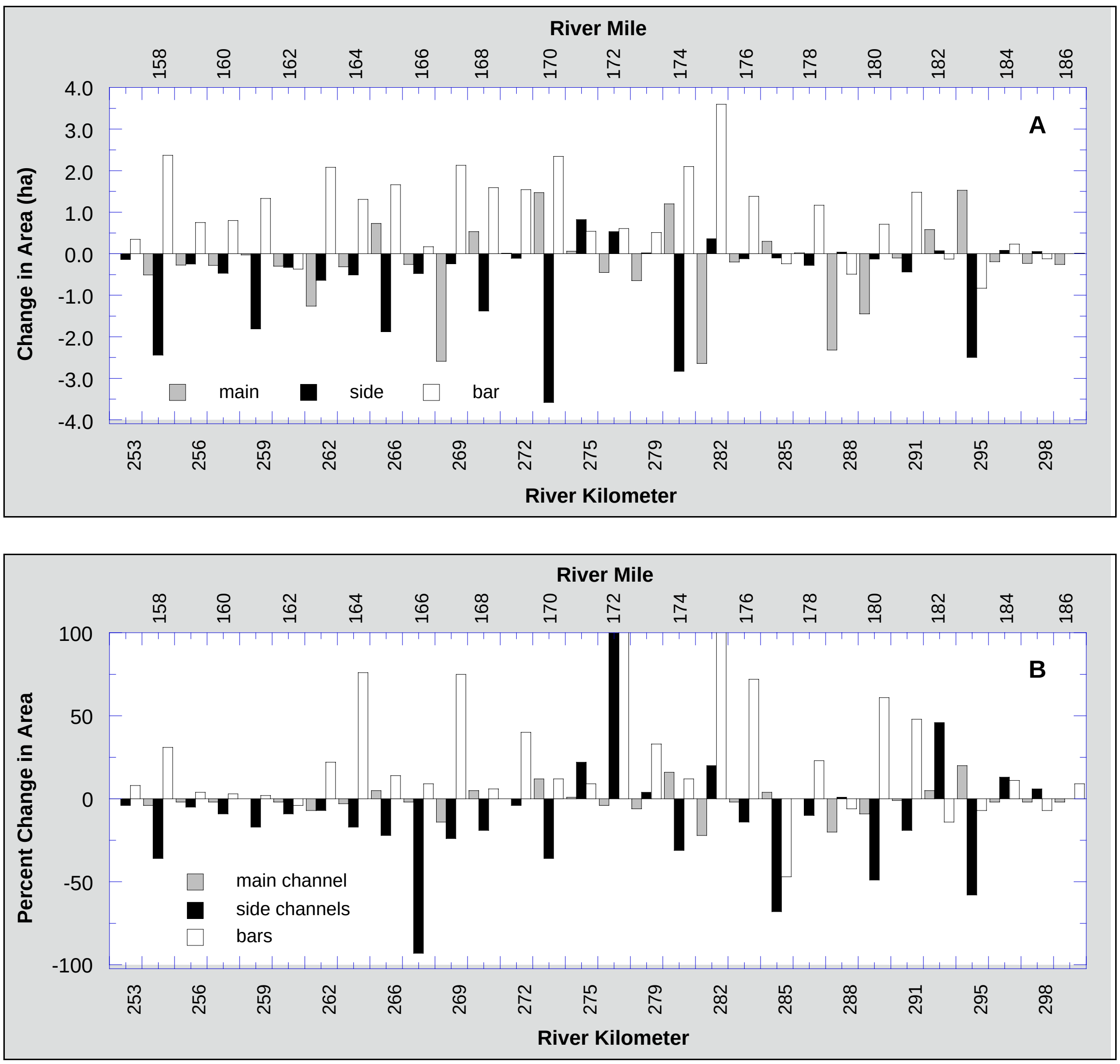


Figure 18. Change in planimetric area of features within the Colorado River; (a) absolute change in area, and (b) change expressed as a percentage of the initial area.

Sediment Transport

Seasonal Trends in Suspended Sediment: Measurements of suspended sediment have been made at USGS gauging stations in the study area periodically from 1976-1999. The length of record and number of observations at these stations varies; however, the complete data set contains hundreds of entries listing water discharge, sediment concentration, and percentage of sand measured in suspended sediment samples. These data were retrieved from the USGS data base and are used here to examine seasonal trends in sediment transport more closely.

Figure 19 plots suspended sediment relations for the Colorado River near Cameo, CO. The panel on the left (Fig. 19a) plots the suspended sediment concentration, C_s (*mg/l*), versus the instantaneous water discharge, Q (m^3/s), with samples distinguished according to whether they were taken prior to or after the peak in the annual hydrograph (rising limb and falling limb, respectively). The panel on the right (Fig. 19b) plots suspended sediment load, Q_s, (*metric tons per day*) versus instantaneous water discharge. The load is calculated from $Q_s = 0.0864\ C_s\ Q$, where the constant 0.0864 is a factor for converting units.

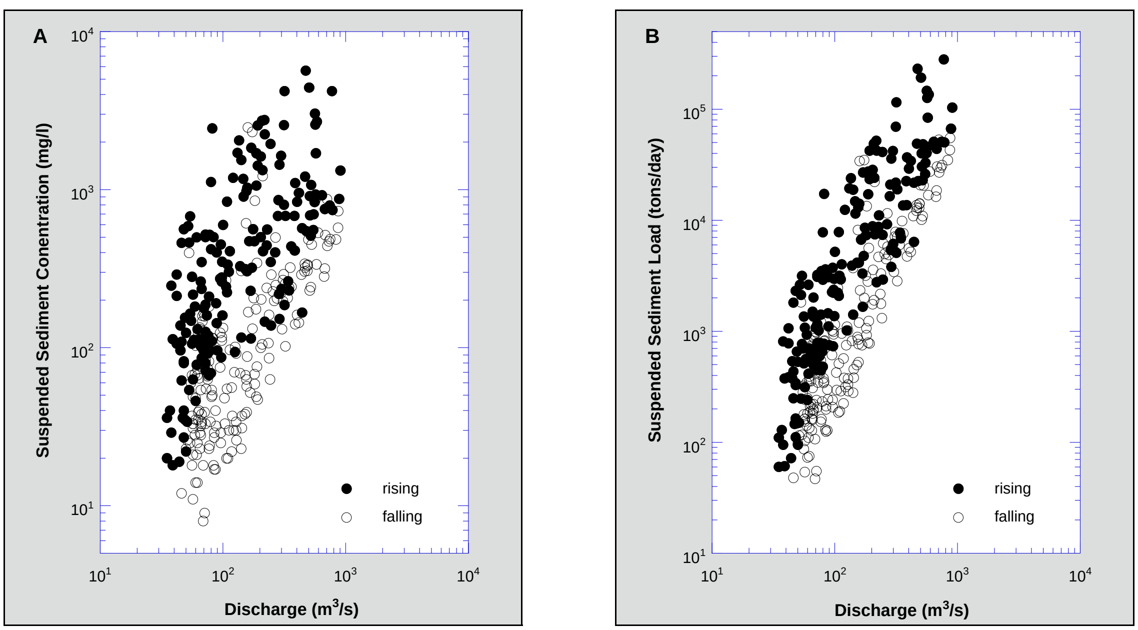


Figure 19. Suspended sediment relations, Colorado River near Cameo, CO; (a) suspended sediment concentration versus discharge, and (b) suspended load versus discharge.

The data in Figure 19a illustrate that suspended sediment concentrations in the Colorado River are generally much higher on the rising limb of the hydrograph than they are on the falling limb. This effect- known as hysteresis- is common to all of the gauges in the study area [*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000]. Suspended sediment loads are likewise consistently higher on the rising limb of the hydrograph than they are on the falling limb (Fig. 19b). The rising-limb flows carry much higher suspended sediment loads because it is during this time (typically in

May) when both sediment concentration and water discharge are high. Suspended sediment concentrations can reach moderately high levels at other times of the year, particularly after late-summer thunderstorms, however, since flows are low at that time of year, these events carry a small proportion of the total annual suspended sediment load.

The data set for the Cameo gauge also includes 449 measurements of the percentage of sand in the suspended sediment samples. Sand includes those sediment sizes falling in the range from 0.065-2.0 mm; sediment finer than 0.0625 mm is silt and clay. Knowing the percentage of sand, the total suspended sediment load can be proportioned between the sand fraction and the silt-clay fraction. Figure 20 shows the same data as in the previous figure, with the suspended sediment load split between silt-clay and sand fractions. The two graphs are plotted at the same scale, thus it is evident that, in general, the silt-clay fraction of the suspended sediment dominates over the sand fraction. On average, 80% of the suspended sediment load of the Colorado River consists of silt and clay. It is also evident in these plots that there is more scatter in the relation between discharge and silt-clay fraction than there is in the relation between discharge and sand fraction. This observation suggests that amount of silt and clay carried in suspension is driven primarily by the supply of fines from sources outside the channel. However, the relation between silt-clay and discharge is not completely random, and it is clear that the amount of fines carried by the Colorado River increases systematically with discharge.

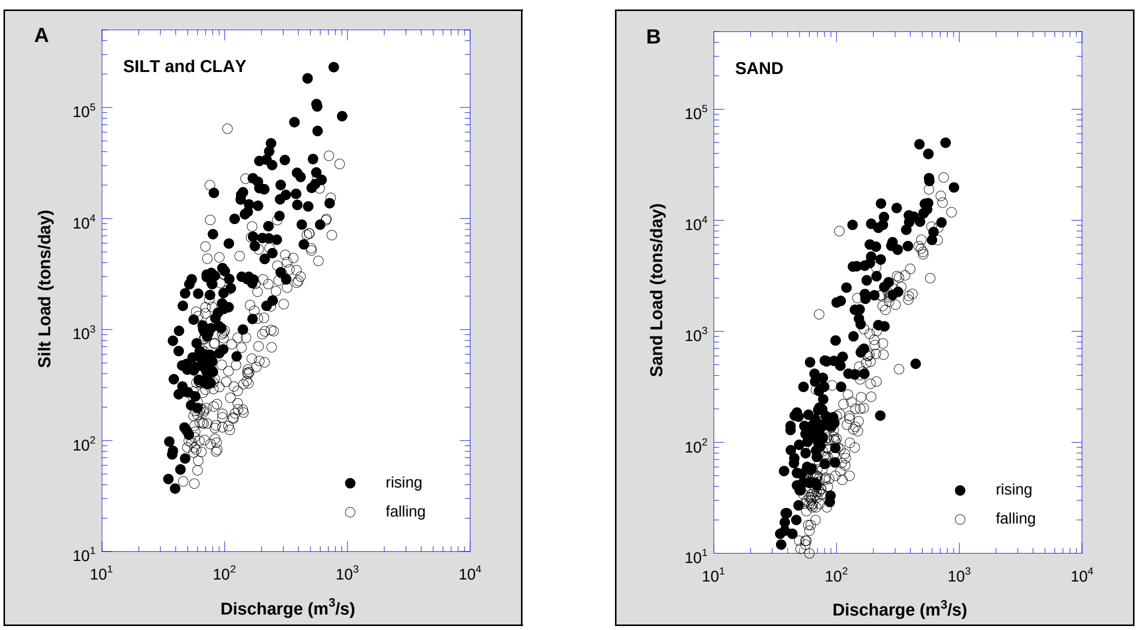


Figure 20. Suspended sediment loads of the Colorado River, near Cameo, CO, weighted by the proportion of (a) silt and clay and (b) sand in suspended sediment samples.

The right panel of Figure 20 shows that there is less scatter in the relation between discharge and sand load, as well as a clearer separation between rising-and falling-limb samples. This observation suggests that sand loads are governed more by flow hydraulics than sediment supply.

Least squares regression of the sand data yields the following relations:

Sand load, rising limb: $Q_s = 0.007Q^{2.35}$ ($r^2 = 0.49$)

Sand load, falling limb: $Q_s = 0.001Q^{2.44}$ ($r^2 = 0.74$)

The exponents in the above relations are similar to each other and lie within the range of values typically observed in alluvial rivers [*Leopold and Maddock*, 1953; *Nordin and Beverage*, 1965]. The difference in coefficients, and the offset in values shown in the preceding figures, suggests one of two things: (i) the supply of sand is generally depleted over the period of the hydrograph, thus the same discharge carries a lower sand load after the peak than prior to the peak, or (ii) the sand available is becoming coarser over the period of the hydrograph, thus less sand is carried in suspension and more sand is moving as bed load, which is not measured. It is not possible to distinguish between these effects without specific data characterizing the evolution of the grain size of the suspended load over the hydrograph. Whatever the case, it is not uncommon for the size distribution of the suspended sediment to change over time as finer or coarser bed material becomes available. For example, measurements taken on the Colorado River in Grand Canyon prior to the construction of Glen Canyon dam show that the grain size of the suspended sediment generally increased on the receding limb of the hydrograph [*Topping et al.*, 2000]. Similarly, sediment measurements and bed material samples taken on the Rio Grande in the 1950s likewise show that both the load and the bed material became coarser over the period of the hydrograph [*Nordin and Beverage*, 1965]. Based on these studies and observations on the Green River (*J. O'Brien*, personal communication), it is likely that the transport patterns in the Colorado River reflect a seasonal redistribution of sand, which moves into temporary storage in pools during low flows, then is remobilized and put into suspension during high flows. If there is a natural tendency for suspended sediment to coarsen with the passage of the hydrograph, then further reduction in the duration of high flows could lead to a significant reduction in the total sediment load of the Colorado River, causing further losses in channel capacity and in-channel habitats.

In order to examine seasonal patterns in flow and sediment transport more closely, synthetic annual time series of discharge and sediment concentration were constructed for the three gauges with the most complete records (Cameo, Whitewater and State Line). The time series were formed by arranging all of the flow and sediment measurements in chronological order from January 1 - December 31, regardless of the year in which they were taken. Figure 21 shows the synthetic time series of discharge and suspended sediment concentration for the Colorado River near Cameo, CO. The irregular patterns reflect the fact that the data are arranged by day of the year, independent of the year. The smooth curve running through the data is fit using a locally weighted least squares method. The trends in this plot show that in typical years the peak in suspended sediment concentration occurs 2-3 weeks prior to the peak in water discharge (Fig. 21a). The distinct mode of high sediment concentration running from early April to late June illustrates that sediment supply and transport are highest at this time.

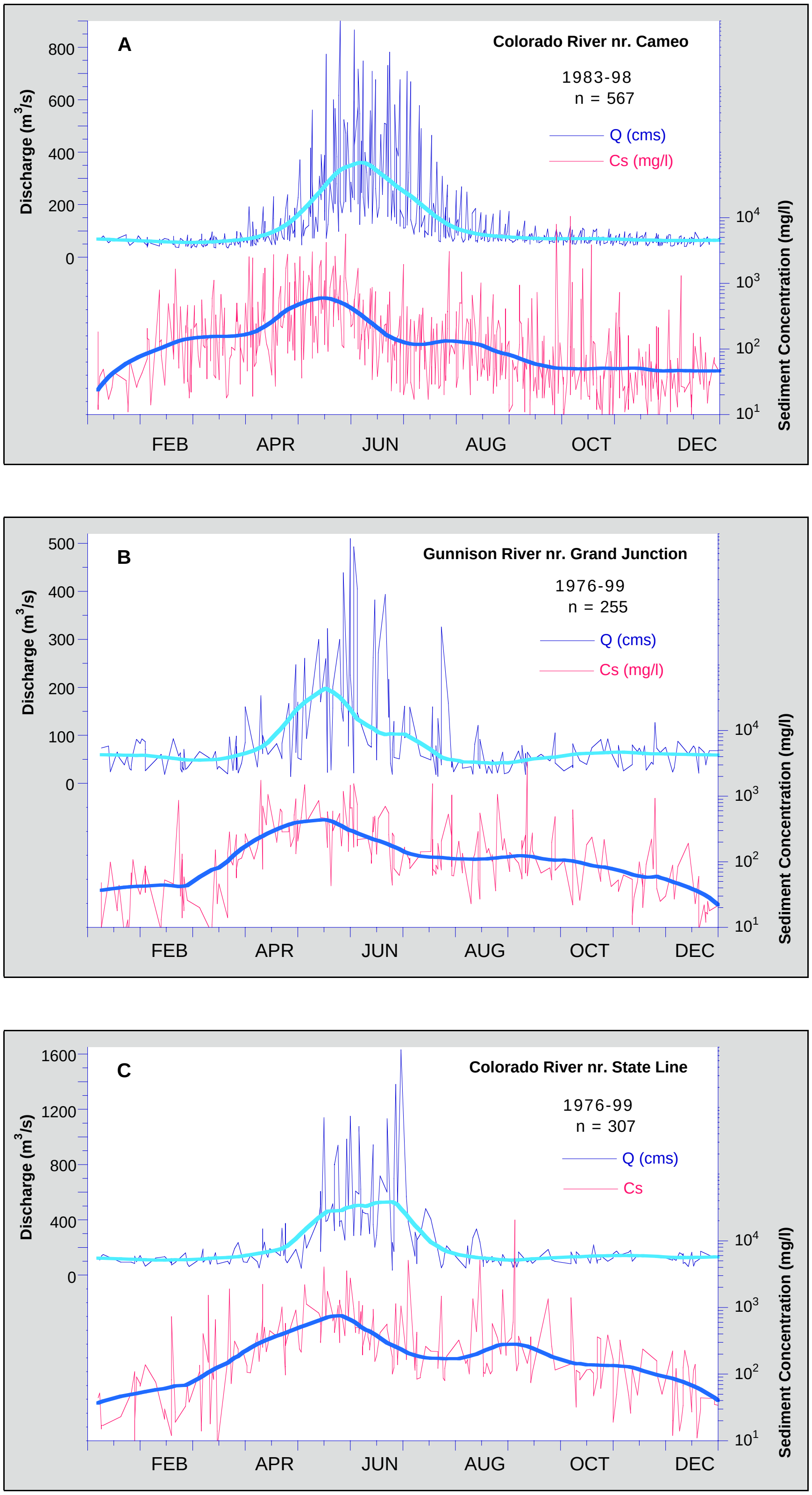
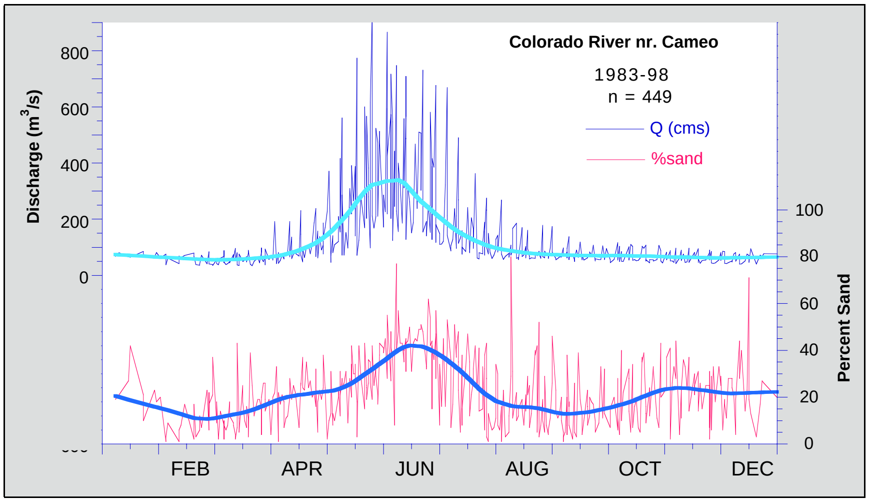


Figure 21. Annual trends in discharge and suspended sediment concentration, (a) Colorado River near Cameo, (b) Gunnison River near Grand Junction, and (c) Colorado River near Colorado-Utah state line (see text for explanation of the data series and trendlines).

Figures 21b and 21c plot similar relations for the Gunnison River and the Colorado River near the CO-UT state line. The patterns observed at these site are similar to those observed at Cameo, although not as clear because there are fewer observations. In both cases there is a period from May through June when sediment concentrations are higher overall, and it appears that the peak in sediment concentration precedes the peak in water discharge by perhaps several weeks.

Figure 22 displays time-series trends in the percentage of sand in suspended sediment samples. In contrast to the trends shown in the preceding figures, it appears that the peak in percent sand occurs 2-3 weeks *after* the peak in water discharge; this trend is particularly evident in the time series for the Cameo gauge (Fig. 22a). The trends at the other gauges are not as well defined, but in both cases it appears that the peak in percent sand follows the peak in water discharge.



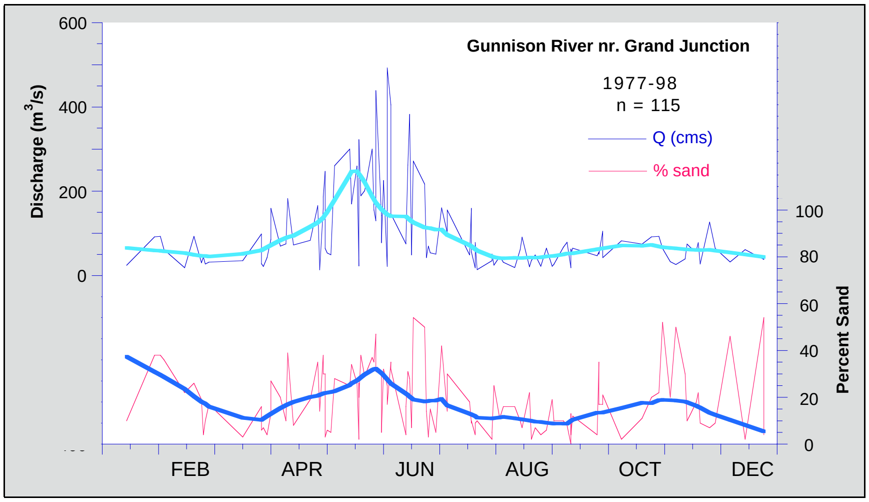
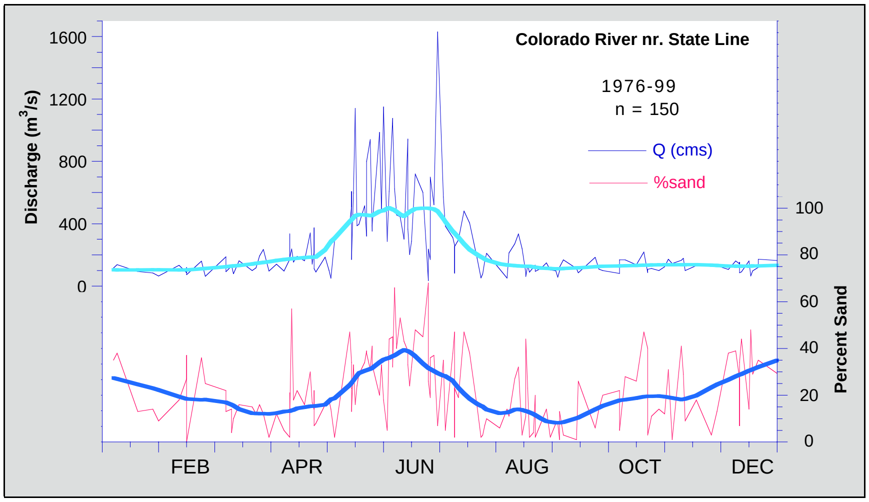


Figure 22. Trends in discharge and percentage of sand in suspended sediment samples, (a) Colorado River near Cameo, CO; (b) Gunnison River near Grand Junction, and (c) Colorado River near Colorado-Utah state line (shown on next page).

Figure 22, continued



The trends in transport shown in the preceding figures indicate that in typical years as much as 40% of the suspended sediment carried by the Colorado River and the Gunnison River consists of sand-sized sediment. In addition it appears that the peak in sand transport follows the peak in water discharge. Very similar trends were observed in measurements of suspended sediment in the Colorado River in Grand Canyon prior to the construction of Glen Canyon dam (*Topping et al.*, 2000), thus the lag in transport appears to be a natural tendency for rivers in this region. If so, it is reasonable to assume that the native fishes have evolved to cope with these conditions. The timing of the peak in sand transport is of potential interest ecologically because it coincides roughly with the period of time when Colorado pikeminnow are preparing to spawn. If flows on the receding limb of the hydrograph decrease rapidly, such that sand drops out of suspension and begins moving as bed load, then it will move much more slowly through the system. This would happen naturally, but it leads to a question whether the transition in transport mode has moved forward in time as a result of water withdrawals and reservoir operations, and if so, does this affect pikeminnow spawning success, or the fishes preferences for spawning in certain areas?

Sediment Trap Data: Streambed sediment traps were installed in riffle and run habitats to monitor the movement of fine sediment (broadly defined) on the receding limb of the hydrograph when Colorado pikeminnow normally spawn. The primary objectives of the trap measurements were to determine the sizes of sediment in transport at that time, and to a lesser extent, to provide qualitative information on transport rates. If one of the goals of coordinated reservoir releases is to flush fine sediment from the bed to improve micro-habitats , then it is reasonable to consider how long the benefits of a flushing flow may last.

The figures on the following page summarize results from the trap measurements. Hydrographs for the period of snowmelt runoff are shown for each of the years in which the traps were used, 1998-2001. The vertical lines on the hydrographs indicate specific dates that the trap samples

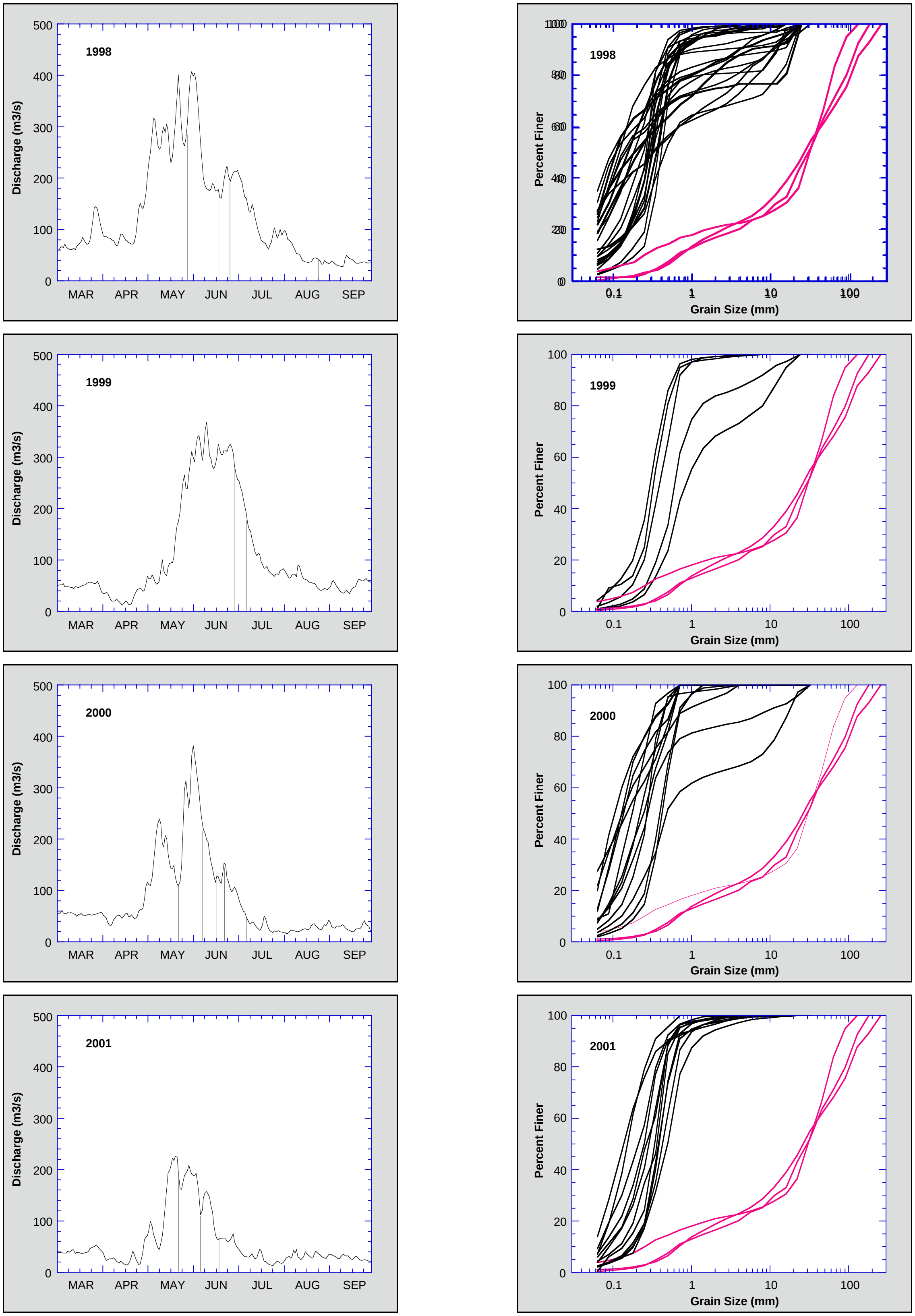


Figure 23. Panels on the left show hydrographs, 1998-2001, with gray lines indicating dates that bed sediment traps were retrieved. Right, size distributions of sediment collected in traps.

were taken. The figures to the right of the hydrographs show the grain size distribution of the sediment taken from the traps; these do not include the first sample of the year, which would include sediment that had accumulated over the previous 9-10 months. For comparison, these figures also show the grain size distribution of the bulk bed material (red lines), as determined from three samples of the subsurface sediment, i.e. the material beneath armor layer.

The first point to note in these figures is that the grain size of the sediment caught in the traps is much finer than the subsurface sediment- the sediment beneath the armor layer. The median grain size of the trapped sediment is often between 0.1 and 0.5 mm (fine-medium sand), whereas the median grain size of the subsurface sediment is about 30 mm (gravel). However, it is evident that the sand-sizes which are common in the traps are also found in appreciable quantities in the bed (up to 20%, depending on size class), indicating that some of the sand caught in the traps exchanges with sand stored in the bed. Sand-sized sediment is thus a non-negligible component of the *bed material load* of the Colorado River, i.e. proportion of the total load which is derived from the bed (the other component–*wash load*- is derived from sources outside the channel and is not found in appreciable quantities in the bed; silt and clay fall into that category in this case).

The second thing to note in these figures is that there was very little sediment coarser than sand ($D > 2$ mm) caught in the traps in years when the peak discharge did not exceed about 300 m^3/s (10600 ft^3/s). This is approximately the flow level that was recommended for producing initial motion of the bed material [*Pitlick and Cress*, 2000]. The presence of fine gravel in samples taken near the peak in 1998 indicates that portions of the bed surface were indeed mobilized during the period of high flow that year. These sizes are not as common in samples collected in subsequent years, suggesting that, at flows less than 300 m^3/s, most of the bed surface remains immobile, as predicted. However, in addition, the data clearly show that even during periods of low flow, the Colorado River continues to transport fine-medium sand ($0.1 < D < 0.5$ mm). In a long-term sense, this has probably always been the case, however, with streamflows now regulated, there are concerns that the build up of fine sediment on the bed of the Colorado River will impair biological productivity [*Osmundson et al*., 2002]. Thus, in addition to moving coarse sediment on the bed surface, another management goal might be to augment receding-limb flows to keep fine to medium sands in suspension over the most productive and important habitats (riffles), particularly during the period when pikeminnow are likely to spawn. The criterion for suspension is based on an relation for estimating the settling velocity, w_s , of natural particles as a function of grain size and shape [*Dietrich*, 1982]. When the fluid shear velocity, $u_* = (ghS_e)^{1/2}$, exceeds the settling velocity of a given size, $u_* > w_s$, then those sizes should be transported in suspension; otherwise they should move as bed load. Using *Dietrich's* [1982] relations for quartz-density sediment with a shape factor of 0.7, the fall velocity for medium sand, $D = 0.5$ mm, is calculated to be $w_s = 7$ cm/s. Based on results from flow modeling in the reach near RK 283 (discussed in the next section), a discharge of 125 m^3/s (4400 ft^3/s) should be sufficient to keep particles finer than 0.5 mm in suspension over riffles.

<u>Evaluation of Flow Hydraulics and Transport Thresholds at RK 283</u>: The reach selected to evaluate the geomorphic effects of augmented and naturally occurring flows is located in the 15-mile reach, about 2 km downstream of the Corn Lake State Wildlife Area and the Highway 141 bridge. The study reach is relatively straight (Fig. 24) with a prominent bar along the left (south) side of the main channel (also shown in the cover photo). The majority of the study reach would be characterized as run habitat. There is a short section of riffle habitat in the middle of the study reach, and a relatively deep pool at the lower end of the reach (Fig. 24). A secondary channel occurs along the south bank; the lower end of this channel becomes a backwater a lower flows. The average bankfull channel width of the study reach is 127 m and the average gradient is 0.0020 m/m.

Water-surface elevations were surveyed through the study reach at eight different discharges ranging from 37 to 394 m^3/s (1300-13900 ft^3/s). These measurements were used with data from the cross-section surveys to determine changes in wetted area of the channel and to calibrate the roughness coefficient in the gradually varied flow model. Table 4 summarizes some of the basic data from measurements at various discharges.

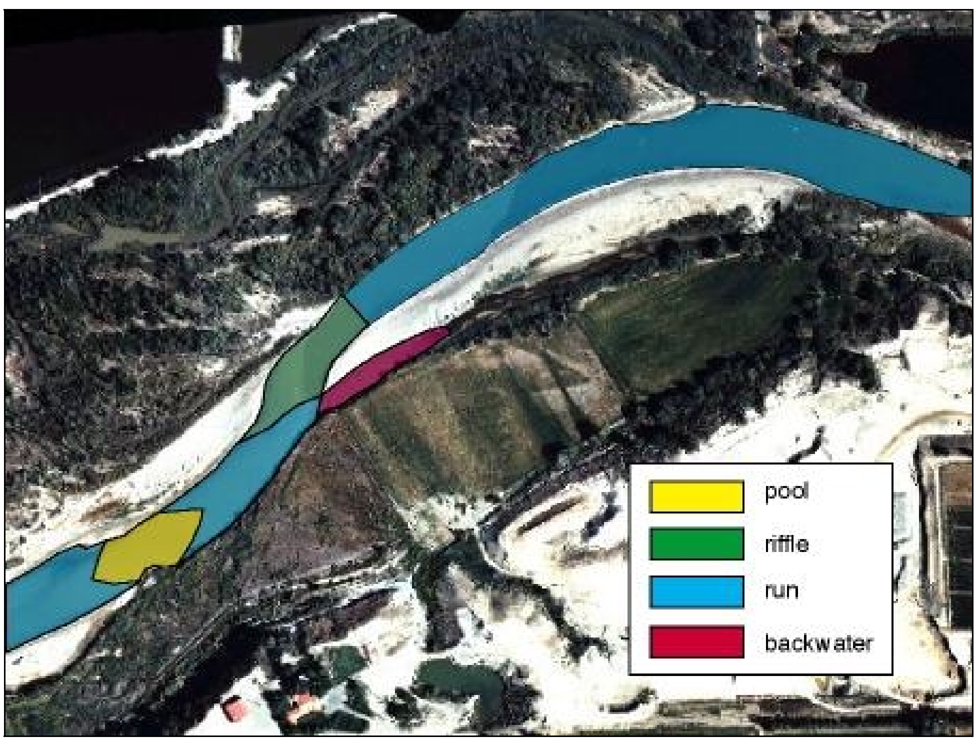


Figure 24. Delineation of in-channel habitats within the RK 283 (RM 176) study reach.

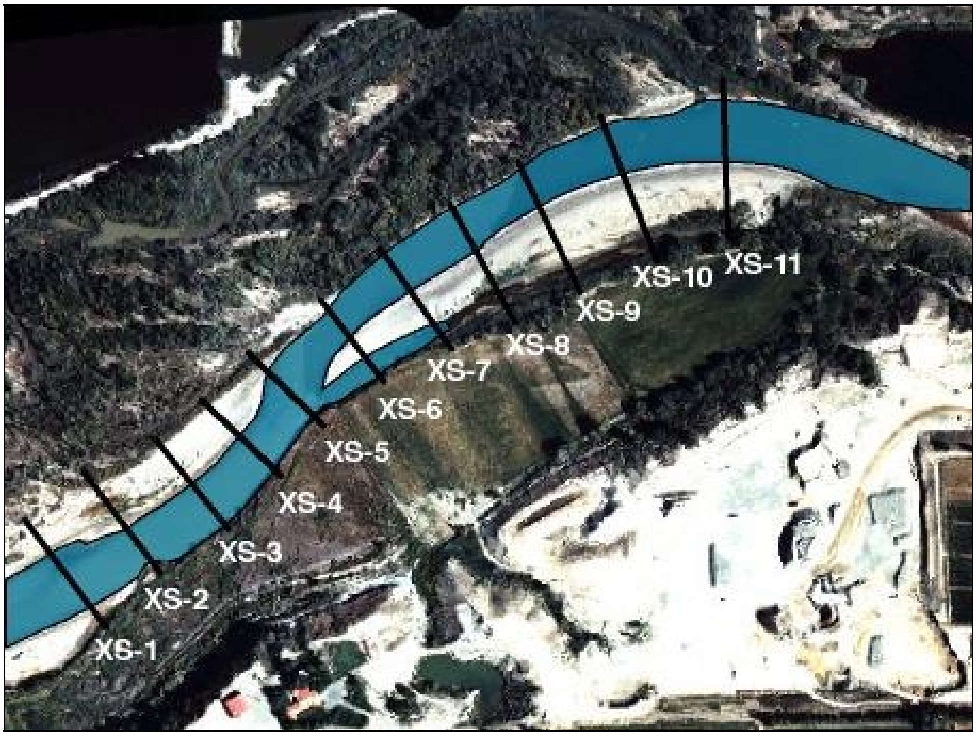


Figure 25. Locations of channel cross sections within the RK 283 (RM 176) study reach.

Table 4. Summary of flow conditions for the range of modeled flows.

Discharge (ft^3/s)	Discharge (m^3/s)	Ratio to Critical Q[1]	Ratio to Bankfull Q[2]	Average Depth (m)	Average Velocity (m/s)	Manning's n
1300	36.8	0.13	0.06	0.85	0.89	0.037
4400	124.6	0.45	0.20	1.25	1.61	0.029
6200	175.6	0.63	0.29	1.30	1.54	0.032
7910	224.0	0.81	0.37	1.43	1.69	0.032
9820	278.1	1.00	0.46	1.41	1.80	0.030
12200	345.5	1.24	0.57	1.57	1.99	0.030
12800	362.5	1.30	0.60	1.57	2.10	0.028
13900	393.6	1.42	0.65	1.63	2.14	0.028

1. Critical discharge is the flow that exceeds the critical shear stress for initial motion of the bed material.
2. Bankfull discharge is the flow that exceeds the threshold for complete mobilization of the bed material.

Flow levels within the study reach were measured at discharges ranging from base flow up to about 2/3 of the bankfull discharge. Hydraulic conditions within the reach vary in a somewhat irregular way as discharge increases over this range. At baseflow, the water-surface width averages 54 m (Fig. 26a), which is less than half the average bankfull width. At this flow the wetted area of the channel is ~40,000 m^2 (Fig. 26b) and more than half of the channel perimeter is dry. Flow stays within the baseflow channel until the discharge reaches approximately 140 m^3/s (~5000 ft^3/s), at which point, the flow begins to inundate bar surfaces, causing a rapid increase in the water surface width and wetted area of the channel (Fig. 26a, b). The width and wetted area increase slowly thereafter; most of the channel bed is inundated once the flow reaches about 280 m^3/s (~10,000 ft^3/s). This flow level corresponds to the threshold for initial motion recommended in the previous reports (*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000)

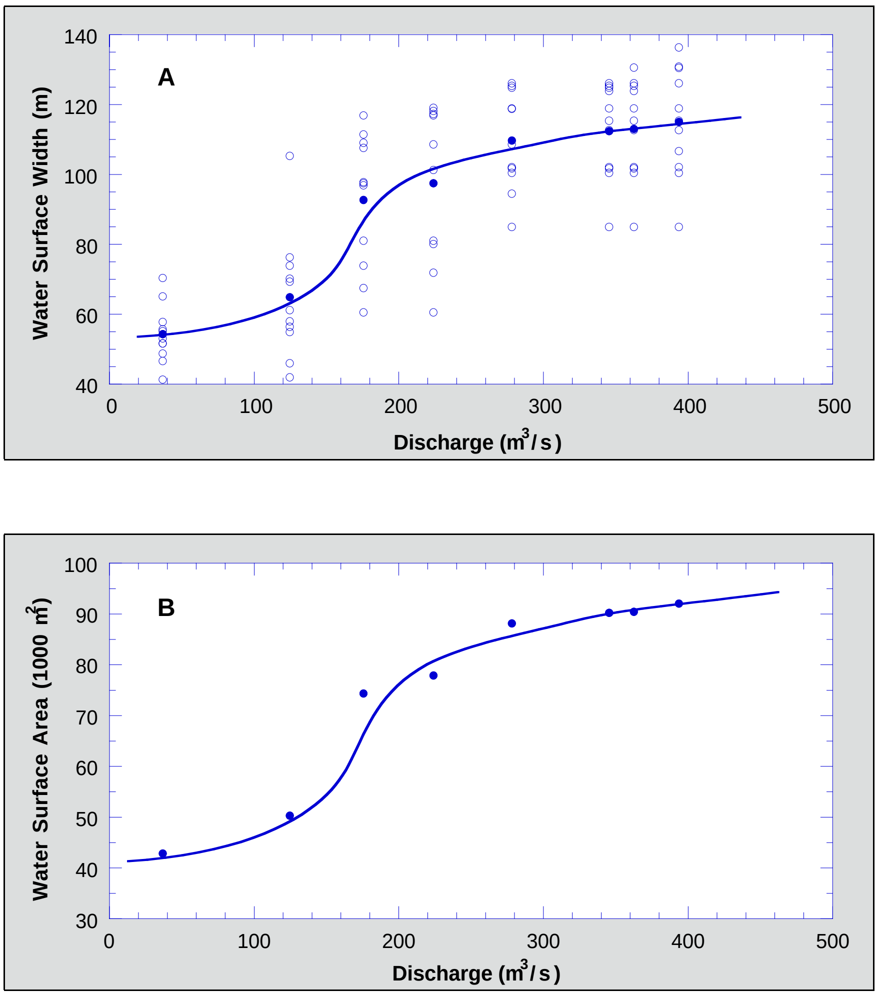


Figure 26. Changes in (a) water surface width and (b) wetted area with discharge, RK 283.

Reach-average estimates of flow depth, h, and flow velocity, U , are plotted as power functions of discharge in Figure 27, forming at-a-station hydraulic geometry relations (*Leopold and Maddock*, 1953). The exponent in the relation for depth (0. 26) is relatively low in comparison to typical values and low in comparison to the value expected for steady uniform flow. The observation that depth changes slowly with discharge reflects the fact that, in this case, width increases rapidly in the range of low to intermediate discharges; in other words, at these flow levels most of the increase in flow volume occurs as a change in width. This effect carries over into the modeled estimates of shear stress, as discussed below. The exponent in the relation for velocity (0.36) is similar to typical values (*Leopold and Maddock*, 1953). Otherwise, it is worth noting the relatively high value of U at Q = 125 m^3/s. This is not an error, but instead reflects locally high velocities produced when most of the flow is contained within the baseflow channel.

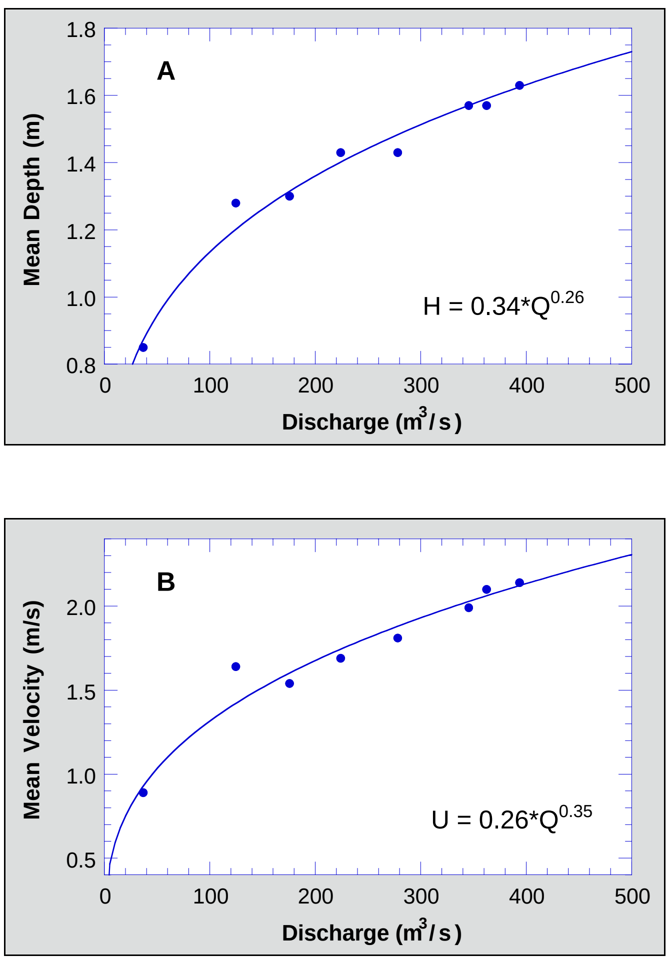


Figure 27. Changes in (a) mean depth and (b) mean velocity with discharge, RK 283.

The one-dimensional hydrodynamic model described earlier was used to calculate flow depths and water surface elevations for each cross section for each of the eight discharges listed in Table 4. The model has one free parameter, Manning's *n*, which was adjusted through trial-and-error until there was reasonably good agreement between modeled and measured water surface elevations. The differences between modeled and measured water surface elevations are generally less than 10 cm, and in a few cases up to 20 cm (Fig. 28).

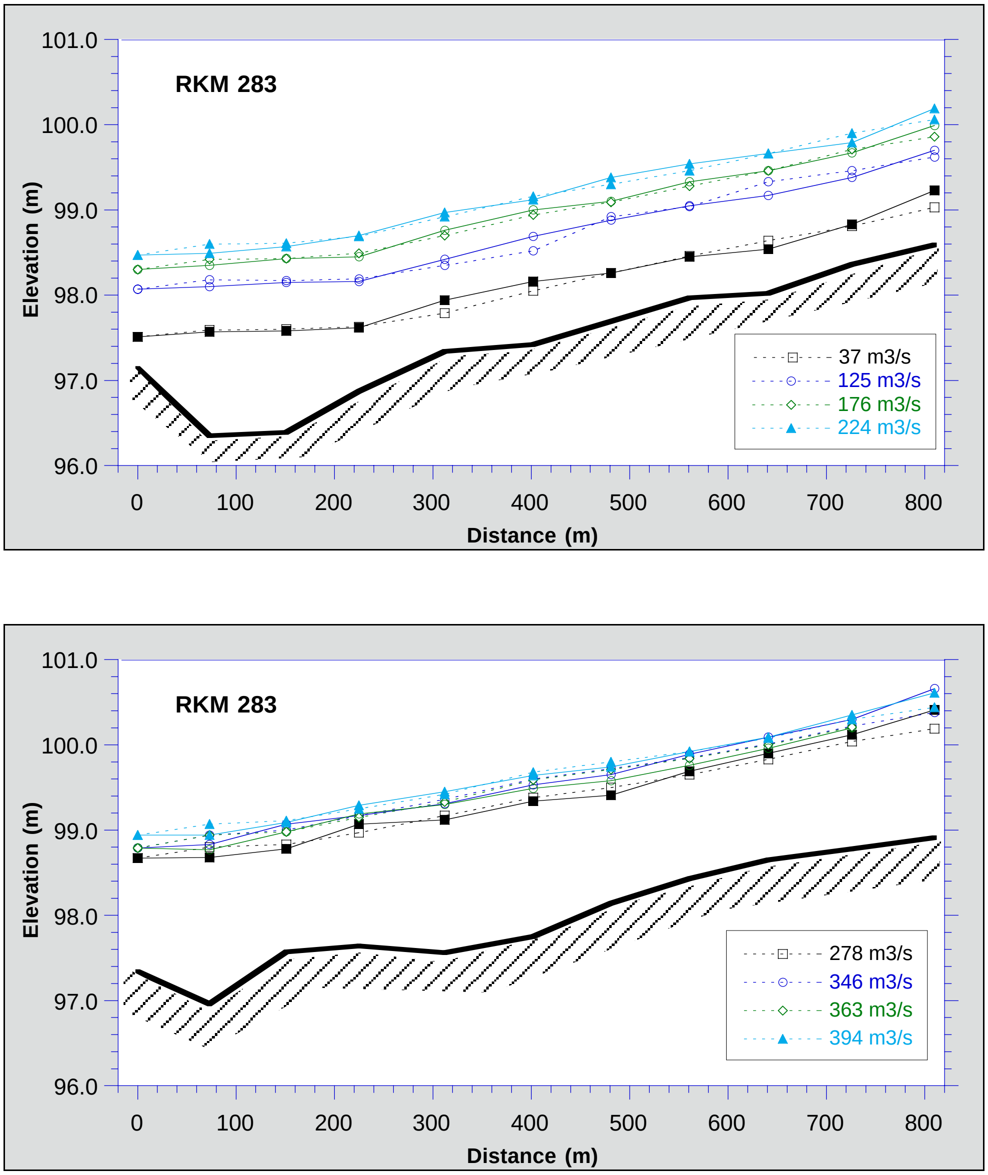


Figure 28. Comparisons between modeled and measured water surface elevations, RK 283. Upper panel shows lower flow levels, lower panel shows higher flow levels. The differences in bed profile in upper and lower panels reflect changes in average bed elevation that occur as higher parts of the channel become inundated; the differences are not due to scour and fill.

As the plots on the preceding page show, the flow depth through the study reach increases rapidly over the range of low to intermediate discharges, and more slowly thereafter. It is also evident that the water-surface profile becomes more uniform as the depth and discharge increase. The adjustments in depth and slope both influence changes in boundary shear stress, τ, which are used as the basis for estimating thresholds for bed load transport. Recall that the boundary shear stress is calculated using equation 3, with the observed depth, h, and the modeled energy slope, S_e. Figure 29 plots the modeled values of boundary shear stress versus discharge for the range of observed flows. The individual points represent the modeled values of boundary shear stress at each of the cross sections in the study reach, and the smooth curve represents the best-fit relation.

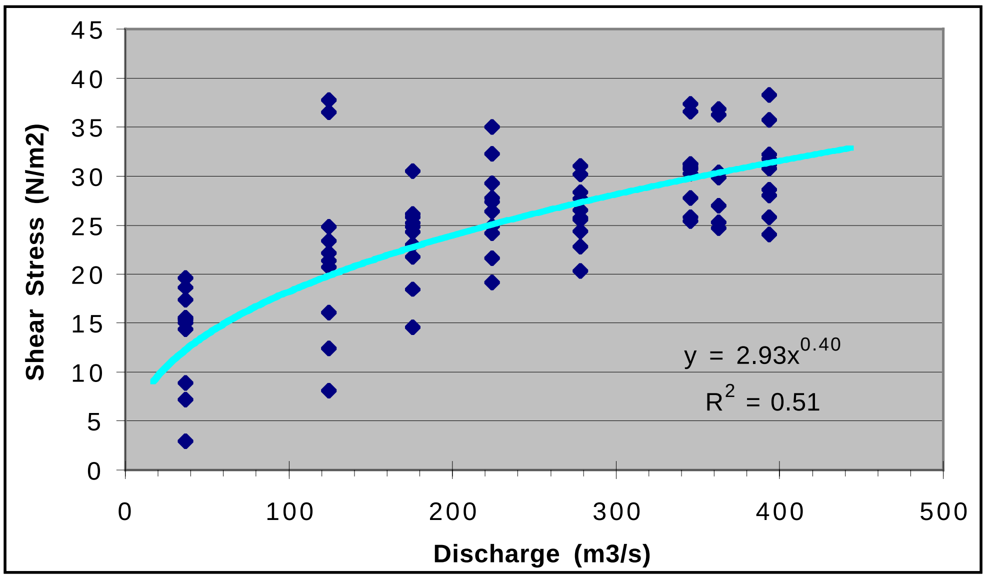


Figure 29. Relation between shear stress and discharge, RK 283

The results shown above indicate that, for a given discharge, the shear stress can vary appreciably from one cross section to another. The greatest range in shear stress occurs at a discharge of 125 m^3/s (4400 ft^3/s), which was the second lowest discharge modeled. At this discharge, nearly all of the flow at the study site is confined within the baseflow channel; locally, this produces relatively high values of mean velocity and shear stress. The two points that lie far above the curve at a discharge of 125 m^3/s correspond to the riffle that spans the channel through cross sections 5 and 6. At this flow, the depth through these sections is only about 1 m; however, because the mean velocity is high (up to 2.5 m/s), the energy slope through these sections is also relatively high, i.e. roughly 50% higher than the reach average. With a slight increase in discharge at these sections, flow begins to overtop the bar surface, causing an abrupt increase in width and roughness, and a corresponding drop in velocity and shear stress. At a discharge of 175 m^3/s (~6200 ft^3/s) the flow through these sections still has an average depth of only about 1 m; however the area of the channel bed that is inundated at this flow is considerably higher, thus the velocity and friction slope decrease and rapidly converge on the reach-average values.

The smooth curve running through the data in Figure 29 defines a reach-average relation for the boundary shear stress as a function of discharge,

$$\tau = 2.93\, Q^{0.40} \qquad (5)$$

where τ is in N/m^2 and Q is in m^3/s; this equation is statistically significant ($r^2 = 0.51$, $p < 0.001$). The exponent in the equation (0.40) is somewhat lower than values derived from field studies in other reaches of the Colorado River, but not anomalous in a hydraulic sense (*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000). This equation can be used with information on grain size to assess previous estimates of the threshold for initial motion, based the relation for dimensionless shear stress, τ^*, given by equation 1. Recall that the relation for τ^* represents a force balance between the fluid stress, τ, acting on the bed versus the resistance provided by the weight of the grains, which scales with their diameter, D. The stress given in the above equation represents the total fluid force averaged over the entire channel reach, thus a reach-average estimate of τ^* can be obtained by balancing this force against the reach-average median grain size, D_{50}. The average D_{50} of the bed surface sediment in the study reach is 0.069 m. Normalizing the individual values of τ by the average D_{50} of 0.069 m (and appropriate constants) gives the relation shown below (Fig. 30). This relation is identical to the one shown above, except in this case the dimensionless shear stress is used as the dependent variable. The coefficient in the best-fit relation changes accordingly but the exponent is the same (0.40).

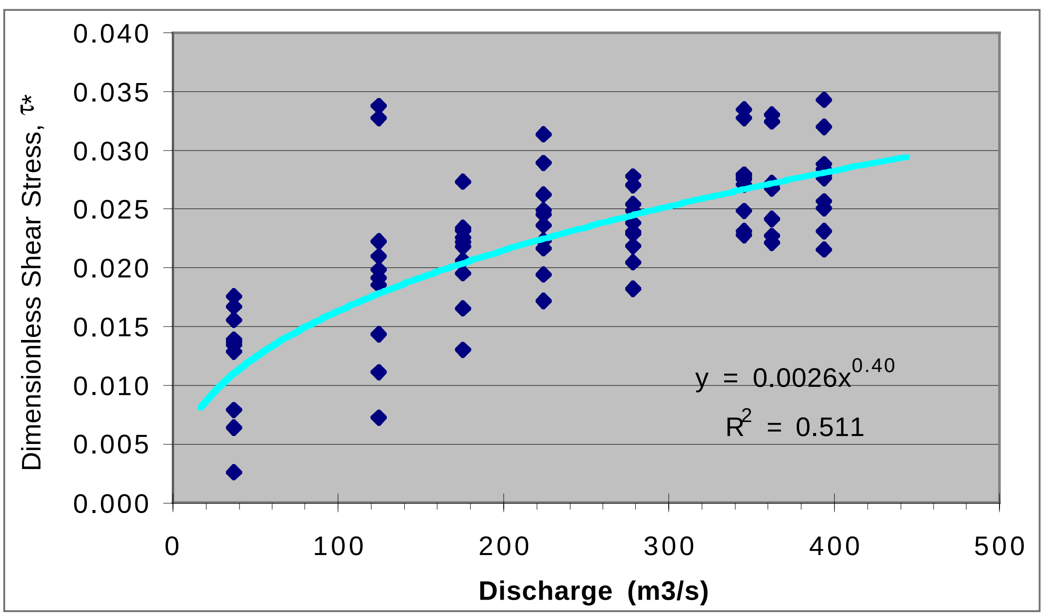


Figure 30. Relation between dimensionless shear stress and discharge, RK 283, assuming no spatial variation bed surface grain size.

The threshold dimensionless shear stress, τ^*_c, for initial motion in this reach was estimated to be 0.025, based on the relation of *Mueller et al.* (2005), using a reach-average slope of 0.002. The relation shown above indicates that this threshold is reached at a discharge of 286 m^3/s (10100 ft^3/s). This value is within 3% of the previous recommended discharge for initial motion, Q_c = 278 m^3/s (9800 ft^3/s) (*Pitlick and Cress*, 2000).

The smooth curve defining the reach-average dimensionless shear stress was developed for a single grain size, which simplifies the analysis, but does not account for the fact that the grain size varies from place to place. Fortunately, during the 2004 drought year streamflows in the 15-mile reach dropped to the point where it was possible to wade the channel and sample the bed surface in all but the very deepest parts of the channel (fine sediment covering higher surfaces on subaerially exposed bars was ignored). These measurements indicate that the bed sediment is generally coarser in the thalweg than it is on the bars, as expected. However, the difference in grain size is not very large, except in the sections spanning the riffle (sections 5-7). The riffle includes many boulders and very large cobbles, leading to a coarse-tailed grain size distribution (D_{50} ~100 mm). In addition there is an short segment of channel between sections 5 and 6 that is floored by bedrock. The presence of bedrock and coarser-than-average sediment within this part of the study reach is indicative of locally high shear stresses produced at certain flows.

Table 5. Comparison of bed surface samples taken from exposed bars and deeper parts of the channel, RK 283. Samples at cross sections 1-5 were taken only across the submerged portion of the channel; samples at the other cross sections were taken across exposed bar surfaces and across deeper parts of the channel.

	morphology	median grain size, exposed bar (mm)	median grain size, thalweg (mm)
XSECT 1	run	60	
XSECT 2	pool	--	
XSECT 3	pool	52	
XSECT 4	pool	59	
XSECT 5	riffle	99	
XSECT 6	riffle	62	80
XSECT 7	run	80	84
XSECT 8	run	76	76
XSECT 9	run	--	--
XSECT 10	run	74	61
XSECT 11	run	--	--

To examine the importance of spatial variations in grain size, the modeled estimates of τ^* were re-calculated using a "local" grain size for each cross section. The local grain size was determined by taking the average of several values, centered around the particular cross section. Calculations for higher flows were based on samples taken from deeper portions of the channel, as well as exposed bar surfaces, since both of these areas would be under water. Calculations for lower flows were based only on samples from submerged portions of the channel. The effect of using spatially variable grain sizes in the model is to reduce the estimates of τ^* slightly, as shown in Figure 31. The inclusion of coarser sediment in certain areas of the channel has the most noticeable effect on flow conditions in the riffle, and then mostly only in the intermediate range of flows from 125 to 224 m^3/s (4400-7900 ft^3/s). At those flows, the shear stress through the riffle is quite high because the energy slope is high; however, when the shear stress produced by those flows is balanced against the coarser bed grain sizes in the riffle, the modeled values of τ^* decrease substantially (Fig. 31). The net effect of using spatially variable (and generally coarser) grain sizes is to reduce the potential for bed load transport at flows much less than about 300 m^3/s (10600 ft^3/s), therefore, that value is retained as the threshold discharge for initial motion.

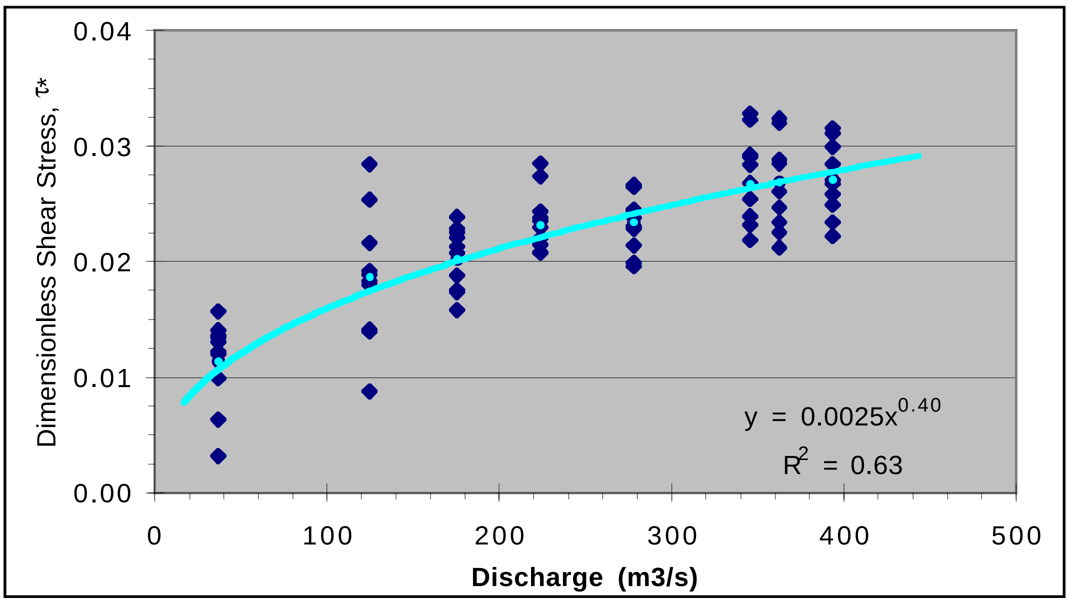


Figure 31. Relation between dimensionless shear stress and discharge, RK 283, after adjusting for spatial variations in grain size.

QUALITATIVE MEASUREMENTS AND OBSERVATIONS

The analysis and results discussed in the preceding sections provide quantitative information on the geomorphic effects of managed and naturally occurring flows in the 15- and 18-mile reaches of the Colorado River. The field surveys and modeling results generally support the results from previous studies and the recommendations given in previous reports. Further evidence of the geomorphic effects of spring flows is illustrated below with ground-based photographs of the channel of the Colorado River taken at various times. The first set of photographs (Fig. 32) shows results from an experiment in 2001 that was used to assess the extent of bed material entrainment within small areas (patches) of the bed. Rectangular patches of the bed surface were washed using a portable water pump and a cordless drill. The surface was then allowed to dry, and the rocks were spray painted with brightly colored paint. Each patch was located with the total station and photographed. The patches were relocated after the peak in snowmelt runoff and photographed again.

Figure 32. Before- and after-photographs of painted rocks at cross section 7, RK 283. The yellow frame measures 50 cm in length by 30 cm in height.

The patch shown above was submerged under about 1 m of water during the peak discharge in 2001 (227 m^3/s or ~8000 ft^3/s). The boundary shear stress in the vicinity of the patch under these flow conditions would have been about 20 N/m^2, which is 30% less than the estimated threshold for motion of the median grain size ($D_{50} \approx 80$ mm at that location). The photographs show that the majority of rocks within the patch did not move. However, it is possible to identify several rocks that appear to have moved, or were transported into or out of the patch during the period of peak flow. This observation is consistent with the expectation that small fractions of the bed surface are mobilized by flows lower than the reach-average threshold for initial motion (assumed to be 50% of the bankfull discharge, or 278 m^3/s). While a discharge of 227 m^3/s falls well short of a “channel maintenance flow”, this flow is capable of mobilizing a handfull of rocks within an area of a few square meters.

The most vivid illustration of discharge-related changes in channel properties within this segment of the Colorado River is the dramatic growth in vegetation on low-lying bar surfaces. Figure 33 compares downstream views of the Colorado River, taken four years apart at the same location on the lateral bar at RK 283. This location was essentially devoid of vegetation in 2000 but is covered with waist-high tamarisk by 2004. The bar surface shown in these photographs was inundated periodically over the period of time covered by the photographs, however, the plants would not have become established if the sediment forming the bed surface had been mobilized to any extent in any of these years. Vegetation growth on these low-lying surfaces is ubiquitous, and provides clear evidence that bed load transport within this reach of the Colorado River is very limited at flows much less than half the bankfull discharge.

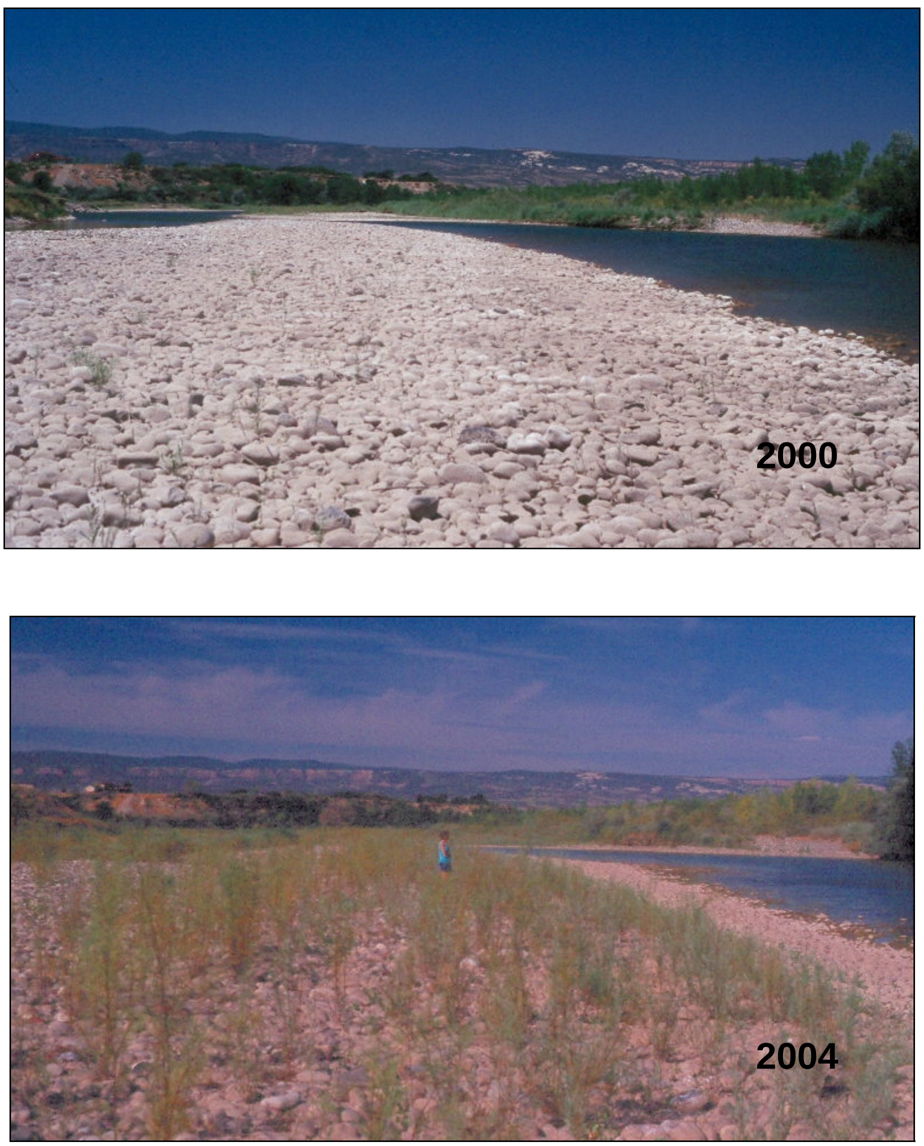


Figure 33. View downstream showing growth of vegetation on the lateral bar, RK 283.

SUMMARY and CONCLUSIONS

This study was initiated to assess how elevated flow levels produced by coordinated reservoir operations in the upper Colorado River basin affect conditions in the 15- and 18-mile reaches. In 1998, the initial year of the study, coordinated reservoir operations were implemented for 7 days. Runoff was allowed to bypass reservoirs, increasing daily discharges into the 15-mile reach by a maximum of about 60 m^3/s (~2100 ft^3/s). Similar procedures were implemented for 10 days in 1999; these flows increased daily discharges in the 15-mile reach by a maximum of about 70 m^3/s (~2500 ft^3/s). The bypass flows were thus successful in boosting background discharges by 10-20%, which was just enough to push flows above the threshold for moving gravel-sized bed material. This is an important result because periodic movement of the bed material is critical for maintaining in-channel habitats within the 15- and 18-mile reaches. However, it is also likely that at these flows the number of gravel- and cobble-sized particles moving is very small, thus limited portions of the bed are reworked. Conditions reflecting widespread entrainment and transport of the bed material (complete reworking) were not evident in 1998 or 1999. It appears that the geomorphic effects of 10-20% increases in discharge at these flow levels are very subtle, and techniques other than those used here would be needed to detect geomorphic change at this scale and over this time period. Limited snowpack and runoff in subsequent years, 2000-2004, prevented further tests of the geomorphic effects of bypass flows.

U.S. Geological Survey analyses of streamflow records in the upper Colorado River basin suggest that water years 2002-2004 were perhaps the driest in the last 100 years. Flows that did occur during the drought period were far below average, thus thresholds for mobilizing cobble- and gravel-sized sediment were not exceeded very frequently. Over the 7-year period of the study, the discharge required to produce initial motion in the 15-mile reach (~1/2 the bankfull discharge) was exceeded for a total of 78 days, which is only about 1/3 of the frequency recommended in previous reports. The discharge required to completely mobilize the bed (bankfull discharge) was never exceeded.

Geomorphic changes in the 15- and 18-mile reaches were monitored using periodic surveys of main-channel cross sections and backwaters, and comparative analysis of aerial photographs taken in 1993 and 2000. These measurements indicate that, overall, the large-scale morphology of the Colorado River has changed little in the last decade. Vertical and lateral deposition of fine sediment occurred in all of the side channels monitored, however, the changes detected in these features were relatively minor.

Analyses of suspended sediment records from gauging stations in the study area reconfirm the importance of late-spring flows for carrying sediment. Concentrations of suspended sediment at all gauging stations are consistently higher on the rising limb of the hydrograph than they are on the falling limb, thus the total annual sediment load is dominated by late-spring flows. Both sediment concentration and water discharge are high in the spring, thus most of the total annual sediment load is carried by flows during this period of time. About 20% of the total suspended sediment load consists of sand. This sediment reaches a peak 2-3 weeks after the peak in water discharge, and not far in advance of the period of time when Colorado pikeminnow are typically preparing to spawn. It is not clear that the sand moving at this time of the year represents a problem in an ecological sense. However, it is evident that the sand has the potential to move either in suspension or in contact with the bed, with the threshold in transport mode occurring at discharges between 125 and 150 m^3/s (4500-5500 ft^3/s).

Intensive field measurements, coupled with results from a one-dimensional hydraulic model, were used to assess variations in flow properties with discharge in a 0.8-km study reach. The field measurements and modeling results indicate that there is a relatively abrupt transition in the water-surface width and wetted area of the channel between discharges of 125 and 175 m^3/s (4500-6200 ft^3/s). At discharges < 125 m^3/s most of the flow is confined to the baseflow channel, and more than half the channel perimeter is dry. At discharges > 125 m^3/s flow begins to cover low-lying bar surfaces, and width increases steadily from there until ~280 m^3/s when most of the channel bed is inundated. This discharge is consistent with flow-modeling results indicating that the threshold for initial motion of the bed material in this reach is exceeded at a discharge of 286 m^3/s. That value is within 3% of the value recommended in previous reports, which was based on flow modeling at a number of other sites, plus analyses of reach-wide trends in channel morphology, average gradient, and bed material properties.

Over the 7-year period of the study, and especially during the 2002-2004 drought, there were few flows high enough to mobilize very much of the bed material of the Colorado River. As a result, native and non-native woody plants, such as sand bar willow, cottonwood and tamarisk, were able to colonize low-lying bars throughout the study area. Plants grew vigorously on bars that would normally be inundated by 1-2 meters of water during the period of spring runoff. The current distribution and health of vegetation on low-lying bars provides the clearest evidence that movement of coarse substrates in the study area was very limited, as these plants would not have become established if there had been appreciable movement of the bed material. It is very likely that some bars will be permanently stabilized as plants become more deeply rooted and grow in size, thus increasing flow resistance and deposition of fine sediment. As time goes on, fluvial-hydraulic processes will compensate for the growth of vegetation by forcing more and more of the flow into the main part of the channel, where it will increase the shear stress and sediment transport rate [*Logan*, 2006]. At some point, the shear stress in the channel will exceed the shear stress for bank stability, and the banks should start to erode, widening the channel. This chain of events assumes, of course, that (a) flows capable of exceeding these stresses will occur at some point in the future, and (b) the channel is not completely constrained by artificial levees or rip-rap. Whatever the sequence of events, the creation and maintenance of habitats used by native fishes will be largely dependent on the frequency and duration of sediment-transporting flows.

RECOMMENDATIONS

The results and observations discussed in this report are broadly consistent with information given in previous reports, although the geomorphic effects of flow levels such as the bankfull discharge could not be assessed since these flows did not occur. The results and conclusions from this study are nonetheless helpful in refining criteria for flows that perform important geomorphic functions, under the assumption that these functions are beneficial to the native fishes and the ecosystem which supports them. The first two recommendations below focus on additional work that might be done to establish the importance of different flow levels on geomorphic processes in the 15- and 18-mile reaches. The third set of recommendations focuses on specific flow levels (magnitude, frequency and duration), and discusses the rationale and intended geomorphic effect of each flow level. The flow recommendations are then summarized in the form of a matrix which can be used to assist federal and non-federal reservoir operators in planning future water-management activities, including bypass flows.

1. Coordinated Reservoir Operations: The coordinated reservoir operations program should be continued and expanded. While it is not easy to quantify the specific geomorphic effects of 10-20% increases in discharge, especially with the low-cost techniques that were used here, there is little question that increases in discharge will increase sediment transport efficiency. Sediment transport rates increase nonlinearly with discharge, thus by moving bypass flows onto the peak, the potential for reworking the channel bed increases, as does the total transport rate. Bypass flows should be coordinated to take advantage of this nonlinearity, and reservoir operations should be modified to boost the peak flow as much as possible, within the shortest period of time. The Recovery Program should continue to pursue the recommendation given in the Phase 2 Report of the Coordinated Facilities Operation Study [*CWCB*, 2003] to augment spring flows by another 20,000 acre-ft, in addition to maximizing releases provided by coordinated reservoir operations. The rationale for increasing the magnitude and duration of the peak is to keep pace with the sediment supply from unregulated tributaries upstream, which does not appear to have changed substantially in the period since 1950 when most of the upper basin reservoirs went on line [*Pitlick et al*. 1999; *Pitlick and Cress*, 2000].

2. Channel Monitoring: The level of information gained from cross section surveys and aerial photographs appears to be too coarse to determine whether 10-20% increases in discharge have measurable effects on the geomorphology of the river channel. More detailed measurements of bed topography and flow characteristics can be made using newer techniques and instruments, including the acoustic doppler current profiler (ADCP); however, field investigations point to a number of problems in using these types of instruments to track spatial variations in bed shear stress and bed load transport rate [*Rennie et al*., 2002; *Gaeuman and Jacobson*, 2005]. Bed load transport can be measured with portable bed load samplers, but sampling is labor intensive and measurements are often restricted to one cross section at a bridge or a cableway. Transport is also highly variable, thus large numbers of measurements need to be taken in order to determine the significance of trends [*Pitlick et al.*, in press]. Perhaps the most cost-effective means for assessing the geomorphic effects of bypass flows is to develop more detailed hydrodynamic models of the reaches of interest. We have worked with the USGS group that developed the Multi-Dimensional Surface Water Modeling System (MD-SWMS) to investigate spatial patterns of shear stress and sediment transport in both small and large channels, including the Colorado River, the Gunnison River and the Williams Fork [*Lisle et al.*, 2000; *Logan*, 2006; *Segura and Pitlick*, 2006; and *Clayton and Pitlick*, 2007]. This approach has its own set of limitations- associated primarily with model calibration- however, once the model is developed and calibrated, it can be used to explore a number of "what-if" scenarios. One application, for example, might be to model how the timing and duration of the peak might affect the flux of sand, which has the potential to move either as suspended load or bed load (see below). Another application might focus on the proportion of the channel bed mobilized by various flows, similar to the work described by *Lisle et al.* [2000] and *Segura and Pitlick* [2006]. The application of a more detailed hydrodynamic model is not likely to lead to different flow recommendations, however, it might help clarify the role that different flows play in structuring habitats used by native fishes and other aquatic organisms.

3. Sand Transport: The sediment data collected in this study are consistent with previous USGS measurements in showing that the Colorado River continues to transport sand well after the peak in the annual hydrograph. Sand has the potential to move either in suspension or in contact with the bed, depending on flow level, thus the mode of transport strongly affects the rate that sand moves through the system. The USGS measurements show that the percentage of sand being carried in suspension typically reaches a peak after the peak in water discharge, at about the same time of year when Colorado pikeminnow are preparing to spawn. It was suggested that spawning success might be affected by a shift in the timing of this transition, with sand dropping out of suspension perhaps earlier now than before. Therefore, the Recovery Program should consider funding additional USGS studies of sediment transport (suspended load and bed load), most likely at the Palisade gauge, but perhaps also at the State Line gauge. These studies should focus not only on trends in sediment concentration, but also on trends in the grain size distribution of the suspended load, as well as the bed load.

4. Flow recommendations: The observations and measurements made over the course of this study reinforce conclusions and inferences made in previous studies (*Pitlick et al*., 1999; *Pitlick and Cress*, 2000), therefore, the target flows recommended for achieving a range of geomorphic effects are retained. The recommendations are listed here as flow categories, with each category having a set of intended purposes, a target frequency and a target duration. The duration and frequency of flows are based on a block of water years, 1978-2000, which are representative of contemporary conditions, absent extreme droughts or further storage and/or depletions (Table 6). The period from 1934-1949 is representative of more natural conditions that existed prior to water development; however, it is known from previous geomorphic studies that the Colorado River was 10-15 % wider then than it is now (*Pitlick et al*., 1999; *Pitlick and Cress*, 2000), thus frequencies of specific discharges are not entirely comparable- a discharge of 600 m^3/s occurring today would fill the channel to the bankfull level, but the same discharge occurring in the 1940s would probably not have reached bankfull, because the channel was wider then. The block of years from 1950-1977 includes the main period of water development, thus much of the runoff produced in the upper basin at that time was likely going into storage as these reservoirs were coming on line. The block of years used in developing flow recommendations thus represents a compromise between conditions, as they were historically, and conditions, as they are now.

Table 6. Frequency of specific discharges for individual time periods. The discharge levels correspond to the recommended flow categories listed below. Frequencies are based on the daily flow record of the Colorado River near Cameo, USGS gauge 09095500.

			Average Annual Frequency of Specific Flow Levels in Different Time Periods (days/year)		
Category	Q (m^3/s)	Q (ft^3/s)	1934-1949	1950-1977	1978-2000
A	608	21500	7	2	5
B	278	9800	44	29	34
C	142	5000	81	63	73

A. Category: Bankfull Discharge

15-Mile Reach: 608 m^3/s (21,500 ft^3/s)

18-Mile Reach: 979 m^3/s (34,600 ft^3/s)

Purpose: Flows that reach or exceed the bankfull discharge are capable of mobilizing most of the framework particles forming the river bed. Entrainment of cobble- and gravel-sized sediment is necessary for maintaining clean substrates, especially in frequently used habitats such as riffles and runs; removal of interstitial fine sediment also improves habitat for benthic invertebrates and other native fishes. Periodic mobilization of the substrate is required to change channel morphology and maintain habitat complexity. Flows exceeding bankfull inundate the floodplain in selected areas. Overbank flows entrain organic matter from the floodplain, thus providing nutrients to stimulate primary productivity. Bankfull flows should occur with sufficient frequency (see below) to maintain the mass balance of sediment, so as to limit deposition in secondary channels, prevent further narrowing of the main channel and limit the growth of non-native vegetation on low-lying gravel bars.

Duration: 5 days per year, averaged over a period of no more than three years

Frequency: No less than one out of every three years

B. Category: Discharge for Initial Motion (approximately one-half the bankfull discharge)

15-Mile Reach: 278 m^3/s (9,800 ft^3/s)

18-Mile Reach: 548 m^3/s (19,400 ft^3/s)

Purpose: Flows equal to one-half the bankfull discharge produce limited entrainment and transport of cobble- and gravel-sized sediment. Silt- and sand-sized sediment that forms a veneer on the bed surface can be brought into suspension, however, entrainment and flushing of fines from the pore spaces (interstices) within the substrate is limited. At this discharge most low-lying bars are covered with a substantial depth of water (many 10s of centimeters), thus most of the bed is inundated. At these flows small numbers of framework grains start to move, and the potential exists to disturb emerging vegetation such as tamarisk. In addition, at this flow level, many secondary channels are inundated, thus the potential exists to flush fine sediment from backwaters.

Duration: at least 30 days per year, averaged over a period of no more than two years

Frequency: No less than one out of every two years

C. Category: Discharge for Suspending Sand in Riffles

15-Mile Reach: 125-150 m^3/s (4,400-5,300 ft^3/s)

18-Mile Reach: 275-330 m^3/s (9,700-11,700 ft^3/s)

Purpose: Discharges in this category are recommended to keep sands finer than about 0.5 mm in suspension over riffles. Riffles provide spawning habitat for Colorado Pikeminnow, thus it is important to keep sands from accumulating on the bed on the falling limb of the hydrograph when spawning normally occurs. This recommendation should be considered provisional, to be evaluated with field data over a period of several years.

Duration: 10 days per year, on the receding limb of the annual hydrograph; in typical years, this would occur in the period from late June to early July.

Frequency: Every year

<u>5. Flow Matrix</u>: A matrix summarizing the above flow recommendations is given on the following page (Table 7). The matrix lists thresholds and durations of discharges that perform important geomorphic functions, and discusses the purposes of different flow levels in terms of the expected geomorphic responses. The matrix can be used by the coordinated reservoir operations group to tailor operations to target multiple objectives of habitat maintenance and creation in alluvial reaches of the Colorado River near Grand Junction.

Table 7. Flow matrix for the 15-mile and 18-mile reaches of the Colorado River.

	Discharge		Flow Conditions and Intended Purposes
Category	15-mile	18-mile	
A	608 m^3/s (21500 ft^3/s)	979 m^3/s (34600 ft^3/s)	o Bankfull discharge: This discharge will mobilize cobble- and gravel-sized sediment on most of the channel bed; widespread mobilization of coarse substrates is required to create and maintain the suite of habitats used by native fishes. o Flows leading up to the bankfull discharge transport a large proportion of the total annual sediment load; maintaining the sediment-transport capacity of the river is the key to limiting further channel narrowing and reduction in habitat complexity. o Flows exceeding the bankfull level inundate limited portions of the floodplain; overbank flows entrain coarse particulate organic matter from the floodplain, providing nutrients to stimulate primary productivity.
Duration: 5 days/year, averaged over no more than three years **Frequency**: No less than one out of every three years			
B	278 m^3/s (9800 ft^3/s)	548 m^3/s (19400 ft^3/s)	o One-half the bankfull discharge: This discharge will mobilize coarse sediment on limited portions of the channel bed; silt and sand deposited on the bed surface can be put into suspension, however, entrainment of fines from within the bed is limited. o This flow inundates most low-lying gravel bars, thus limiting the growth of woody plants, especially tamarisk, that can stabilize channel bars once they become established o Most of the channel perimeter is inundated by this flow; the increase in wetted area provides additional habitat for aquatic organisms, including native forage fishes, and benthic invertebrates.
Duration: at least 30 days/year, averaged over a period of no more than two years **Frequency**: No less than one out of every two years			
C	125-150 m^3/s (4400-5300 ft^3/s)	275-330 m^3/s (9700-11700 ft^3/s)	o Approximately one-fourth of the bankfull discharge: Discharges in this range are needed to keep fine-medium sand in suspension over riffles. Concentrations of suspended sand appear to reach a peak after the peak in water discharge, roughly at the time of year when Colorado pikeminnow are preparing to spawn. o Riffles provide spawning habitat for Colorado pikeminnow; it is important to keep sand from accumulating on the bed during the period of spawning to increase spawning success. o Sand can move in either in suspension or in contact with the bed; sand moving in contact with the bed moves more slowly through the system, increasing the tendency for fines to accumulate in the bed, potentially limiting native fishes use of riffle and run habitat.
Duration: 10 days per year, on the receding limb of the hydrograph **Frequency**: Every year			

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